**IN THE UNITED STATES COURT OF FEDERAL CLAIMS**

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| IN RE DOWNSTREAM ADDICKS AND BARKER (TEXAS) FLOOD-CONTROL RESERVOIRS | Sub-Master Docket No. 17-cv-9002L |
| | Chief Judge Susan G. Braden |
| THIS DOCUMENT RELATES TO: | |
| ALL DOWNSTREAM CASES | |

**UNITED STATES' MOTION TO DISMISS FOR LACK OF JURISDICTION AND FOR FAILURE TO STATE A CLAIM UPON WHICH RELIEF CAN BE GRANTED**

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## INTRODUCTION

Hurricane Harvey was the greatest single rainfall event in United States history. The National Weather Service has concluded that the storm was a 1000-year event. Ex. 1, National Weather Service National Hurricane Center Tropical Cyclone Report, Hurricane Harvey at NOAA0000007. The storm made landfall as a Category 4 hurricane on August 25, 2017, and over the next several days dumped an estimated one trillion gallons of water in the Greater Houston area. Harris County estimates that the storm produced enough rain to cover a 1,800 square-mile area with thirty-three inches of water.[1] According to Harris County, more than 120,000 structures flooded, including around Buffalo Bayou. *Id. See also* Consol. & Am. Downstream Master Complaint ¶¶ 59, 61-66, ECF No. 23 ("Compl."). The people of Houston suffered substantial losses in this storm.

The Greater Houston area has long been subject to devastating floods. After severe flooding in the early twentieth century, the United States constructed flood-control projects in and around the City of Houston, including two flood-control dams: the Addicks and Barker dams. These dams were constructed in the 1940s, are located about seventeen miles west of downtown Houston, and have substantially reduced flooding risks for the past 70 years. Indeed, their presence has facilitated the growth and development of modern-day Houston, now the fourth largest city in the United States.

Before, during and after Hurricane Harvey, the United States sought to prevent loss of life and ameliorate the damage to private property that is inevitable when such an extraordinary Act of God strikes. After the storm made landfall, but while it still raged, military and civilian personnel in the United States Army Corps of Engineers ("Corps") monitored water levels at the

[1] *See generally* https://www.hcfcd.org/hurricane-harvey

Addicks and Barker dams and observed unprecedented inflows. Rain continued to fall hour after hour, and at the Addicks and Barker dams, flood waters continued to rise higher and higher. The District Commander in charge of the reservoirs announced on August 28, 2017: "If we don't begin releasing now, the volume of uncontrolled water around the dams will be higher and have a greater impact on the surrounding communities." Ex. 2, Corps Press Release (Aug. 28, 2017) (internal quotation marks omitted). The Corps took action in order to deal with the emergency.

As soon as storm waters began to recede, countless Americans mobilized to provide essential support to those impacted by Harvey. For its part, the United States, through the Corps, the Federal Emergency Management Agency ("FEMA"), the Small Business Administration ("SBA"), the Department of Housing and Urban Development ("HUD"), and other government agencies, brought aid to the hurricane's victims and began facilitating recovery efforts. Those efforts are ongoing; the United States has thus far allocated billions to those affected by Hurricane Harvey. *See* Additional Supplemental Appropriations for Disaster Relief Requirements Act, Pub. L. No. 115-72, 131 Stat. 1224 (2017); Reinforcing Education Accountability in Development Act, Pub. L. No. 115-56, 131 Stat. 1129 (2017); Hurricanes Harvey, Irma & Maria Education Relief Act of 2017, Pub. L. No. 115-64, 131 Stat. 1187; Disaster Tax Relief & Airport & Airway Extension Act of 2017, Pub. L. No. 115-63, 131 Stat. 1168 (collectively providing tax relief, education relief, and other assistance to disaster victims). Additionally, two weeks ago, Congress appropriated another $90 billion to further promote recovery efforts in areas throughout the United States affected by major disasters in 2017. Bipartisan Budget Act of 2018, Pub. L. No. 115-123, 132 Stat. 64. A significant portion of these funds is intended for individuals and businesses harmed by Hurricane Harvey. Specifically, each qualifying property owner affected by Hurricane Harvey can seek individual assistance from

FEMA in an amount up to $33,300 to cover home repairs, serious needs, or expenses associated with the hurricane.[2] In addition to this aid, each qualifying property owner may be eligible to receive low-interest SBA loans (up to $200,000 for residential property and up to $2 million for business property, including rental properties).[3] That aid has been flowing and continues to flow to property owners, such as Plaintiffs, who are residents of the hurricane-ravaged counties.

The United States has been sued by more than 1,500 plaintiffs, who contend that the Corps' emergency response to Hurricane Harvey constitutes a Fifth Amendment taking because their properties were damaged by flooding and floodwaters that flood control improvements could not prevent. These constitutional claims are unprecedented. Never in the history of the Republic has the Supreme Court or an appellate court found the Fifth Amendment to require the United States to pay compensation to persons damaged by catastrophic flooding caused by a major hurricane. Couched as tort suits, such claims would clearly fail. *See, e.g., Katrina Canal Breaches Consol. Litig.*, 696 F.3d 436 (5th Cir. 2012). Plaintiffs should fare no differently under a constitutional taking theory.

<u>First</u>, Plaintiffs fail to identify in their Complaint a way that the Corps could have operated the Addicks and Barker dams that would have protected privately-owned property both above and below the dams. Plaintiffs do not even contend that such protection was possible. Instead, Plaintiffs implicitly maintain that the Corps should have directed floodwaters elsewhere—elsewhere being on to some other person's private property—in order to protect

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[2] Temporary housing or permanent housing construction repair, whereby FEMA performs direct repairs to fix homes—instead of giving money—may also be available to eligible property owners.

[3] *See* https://disasterloan.sba.gov/ela/Declarations/DeclarationDetails?declNumber=1008079&members=false.

Plaintiffs' own property. Plaintiffs themselves assert the "water pools in the reservoirs rose faster than expected," leaving the Corps with only two options: "release water from the dams and flood the downstream properties, or risk exceeding the reservoir system's capacity and flooding other communities." Compl. ¶ 64. But the Fifth Amendment is not a constitutional flood insurance policy. No taking arises where, as here, the government is merely acting to mitigate or minimize an inevitable harm to the public. *See, e.g., Miller v. Schoene*, 276 U.S. 272, 279-80 (1928).

Second, under both Texas and long-standing federal law, Plaintiffs lack a protected interest in the property purportedly taken. Texas law does not recognize a property right to keep land downstream of a flood-control dam free from floodwaters during an extreme storm, especially when the dam was neither built nor modified after the property was acquired. And the Flood Control Act of 1928, which was in place long before Plaintiffs purchased their property, establishes as a background principle that protection from floodwaters such as those produced by Harvey is not a stick in the bundle of rights possessed by Plaintiffs. *See* 33 U.S.C. § 702c.

Third, Plaintiffs' claims should be dismissed for lack of jurisdiction. Plaintiffs do not allege facts that, if proven, would establish a pattern of severe and recurrent flooding that was intended and effected by the United States. Consequently, their allegations do not rise to the level of a compensable taking, but constitute, at most, a tort claim for which this Court lacks jurisdiction. *See, e.g., Portsmouth Harbor Land & Hotel Co. v. United States*, 260 U.S. 327, 329-330 (1922); *Ridge Line, Inc. v. United States*, 346 F.3d 1346 (Fed. Cir. 2003). Both the government actions alleged and the flooding claimed resulted from a Category 4 hurricane—not an intentional act by the United States.

Fundamentally, Plaintiffs ask this Court to transform the United States into an "insurer that the evil of floods be stamped out universally[,]" in contravention of longstanding Fifth Amendment jurisprudence. *United States v. Sponenbarger*, 308 U.S. 256, 266 (1939). Accordingly, pursuant to Rules 12(b)(1) and 12(b)(6) of the Rules of the United States Court of Federal Claims ("RCFC"), the United States moves to dismiss Plaintiffs' Consolidated and Amended Downstream Master Complaint for lack of subject matter jurisdiction or in the alternative for failure to state a claim upon which relief can be granted.

## FACTUAL BACKGROUND [4]

The City of Houston has long been subject to severe flooding because of its flat terrain and clay-like soils. *See generally* Jim Blackburn & Larry Dunbar, *Houston's High Water Problems*, 46-DEC Hous. Law. 18, at *19 (2008) (noting that "flooding and drainage have always been problems in Houston."); Ex. 3, H. R. Doc. No. 75-456, at 2(1937) (describing how floods in the area "result from the rapid run-off of heavy precipitation . . ." that inundate areas in and above Houston). Following a severe flood in 1935, Congress directed the Chief of Engineers to study flood protection along Buffalo Bayou, a waterway flowing through Houston to the Houston Ship Channel and ultimately the Gulf of Mexico. Rivers and Harbors Act of June 20, 1938, Pub. L. No. 75-684, 52 Stat. 802, 804 (codified at 33 U.S.C. § 540 (2017)). That investigation showed that hurricanes had caused flooding of up to 40 feet at Main Street in Houston, Texas and that flood control structures were necessary to protect life and property.

[4] The United States has cited throughout this motion background facts concerning Hurricane Harvey and the Houston area. The Court has discretion to take judicial notice of these facts. *E.g. Rio Grande Silvery Minnow v. Keys*, 469 F. Supp. 2d 973, 988 n.12 (D.N.M.) (taking judicial notice of weather conditions readily determinable), *vacated on other grounds by* 601 F.3d 1096 (10th Cir. 2002). But, judicial notice is not necessary in this circumstance because the background facts do not control the outcome of any of the legal arguments supporting dismissal of Plaintiffs' claims.

> The loss of life, heavy property damage, and disruption to the commerce of the city and port of Houston occasioned by the flood of 1935 have demonstrated the urgent need for the prosecution of comprehensive and effective measures for the control of future floods in Buffalo Bayou.

Ex. 3 at USACE000004.[5] Congress and Harris County then approved a plan by the Corps for the construction of the Addicks and Barker dams, which were completed in 1948 and 1945, respectively. Compl. ¶¶ 56, 38; 52 Stat. 802, 804.

The Addicks and Barker reservoirs were built to provide flood control downstream, including in areas where Plaintiffs are located, and had been in place for decades before Plaintiffs acquired their properties between 1975 and 2017.[6] *See* Compl. ¶¶ 35, 42, 52. Since the dams were constructed, the city of Houston has grown to 2.3 million residents.[7] Neither the Corps nor the federal government authorized or permitted the downstream development nearby to Buffalo Bayou. The dam projects were successful and indeed, the majority of Plaintiffs allege that their properties had never flooded prior to Hurricane Harvey. Compl. ¶¶ 7-8, 10-33; 35-42; 44-46. During Hurricane Harvey, the dams withstood tremendous inflows and remained intact.

Hurricane Harvey was the first Category 4 hurricane to make landfall on the continental United States since 2004. From August 25 to 29, 2017, Hurricane Harvey inundated Houston with rains that shattered local records and caused widespread flooding in the Houston metropolitan area. Compl. ¶¶ 59-60. The hurricane's flooding led Texas's Governor to declare

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[5] The 1935 flood resulted from a 3-day rainfall total of between twelve and fifteen inches. Ex. 3 at USACE000003.

[6] Some plaintiffs alleged in their original complaints that they acquired their properties before 1989, but none are named in the master complaint. None alleged they acquired their properties before the dams were constructed.

[7] *See* https://www.census.gov/quickfacts/fact/table/houstoncitytexas,harriscountytexas/PST045216

emergencies in sixty counties.[8] The President of the United States, likewise, declared the hurricane a major disaster.[9]

During Hurricane Harvey, consistent with the flood-control purposes for which the dams were constructed, the Corps operated the dams to attempt to prevent loss of life and ameliorate harm to the general public.[10] As in any heavy rain event, the Corps initially closed the floodgates to detain water in the reservoirs and protect downstream communities from flooding. *See* Compl. ¶ 59. But as water levels in the Addicks and Barker reservoirs rose from the unprecedented rains and water began to flow around the end of one dam, the Corps was forced to begin releasing water in the early morning of August 28, 2017.[11] Even with the releases, because of the storm's record-setting rains, inflows into both reservoirs greatly exceeded outflows and water levels in the reservoirs continued to rise.

As floodwaters from Hurricane Harvey receded, the Corps deployed hundreds of employees from its Texas and other offices to work with local governments to protect the life, health, and safety of those affected by the hurricane.[12] The Corps helped FEMA provide temporary power and housing, and otherwise worked to make sure critical public facilities were operational. *Id.* FEMA deployed more than 21,000 personnel in support of Hurricane Harvey

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[8] *See* https://gov.texas.gov/news/post/diaster-proc

[9] *See* https://www.fema.gov/disaster/4332

[10] *See* http://www.swg.usace.army.mil/Media/News-Releases/Article/1346048/addicks-and-barker-reservoirs-floodwaters-discharged-ready-for-next-rain-event/

[11] *See* http://www.swg.usace.army.mil/Media/News-Releases/Article/1291369/corps-releases-at-addicks-and-barker-dams-to-begin/

[12] *See* http://www.usace.army.mil/Hurricane-Harvey-Response/. Countless private citizens, too, bravely came to the heroic rescue and aid of thousands of Texans harmed by Harvey.

response, including search and rescue teams to help those stranded, and transporting medical supplies and equipment including meals and water. The United States expects to expend billions of dollars to provide aid and facilitate the recovery of persons affected by the storm. Thus far, for Harvey related damage, FEMA has received more than 370,000 requests for assistance and has approved $1.55 billion pursuant to the Individual and Households Program.[13] The October 26, 2017 Additional Supplemental Appropriations for Disaster Relief Requirements Act, Pub. L. No. 115-72, appropriated $18.67 billion to FEMA, including funding that can be issued as direct loans to local governments providing essential services as a result of Hurricane Harvey and other natural disasters. The SBA has already awarded more than $3.2 billion in Hurricane Harvey-related aid. HUD also expects to issue additional hurricane aid to those eligible.[14]

Plaintiffs can apply for many of the various types of federal aid available to them and to the tens of thousands of other property owners whose properties flooded during the hurricane. This is the traditional Congressionally-approved method by which landowners harmed by an extraordinary natural disaster like Hurricane Harvey receive federal assistance.

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[13] *See* note 9. The Individual and Households Program provides aid to those affected by a disaster who have uninsured or underinsured expenses and serious needs, and can include rental assistance for temporary housing or home repair or replacement assistance. *See https://www.fema.gov/media-library-data/1502371943459-711a17671708a7ded53f0b22315f2597/FACTSHEETIndividualsandHouseholdIHP.pdf*

[14] In addition to the agencies listed here, the Corporation for National and Community Service, Department of Health and Human Services, Department of Homeland Security National Protection and Programs Directorate, U.S. Coast Guard, Defense Logistics Agency, U.S. Department of Agriculture, National Guard Bureau and other agencies have provided extensive additional assistance and aid.

## LEGAL BACKGROUND

### I. Standard of Review

With respect to a motion to dismiss for failure to state a claim upon which relief may be granted, a court must accept as true all the factual allegations in the complaint, but not the legal allegations. *Sommers Oil Co. v. United States*, 241 F.3d 1375, 1378 (Fed. Cir. 2001) (citations omitted). In opposing such a motion, the plaintiff must demonstrate that the complaint contains sufficient facts to "state a claim to relief that is plausible on its face," and that the court may "draw the reasonable inference that the defendant is liable for the misconduct alleged." *Ashcroft v. Iqbal*, 556 U.S. 662, 663 (2009) (quotations and citations omitted). Moreover, the allegations must set forth facts that demonstrate the plaintiff is plausibly entitled to the relief sought, rather than mere legal conclusions absent supporting facts. *Id.*

Federal courts are courts of limited jurisdiction and they are presumed to lack jurisdiction in a particular case unless jurisdiction is established by the plaintiff. *See Renne v. Geary*, 501 U.S. 312, 316 (1991). On a motion to dismiss, the plaintiff bears the burden of proving that subject matter jurisdiction is appropriate by a preponderance of evidence. *See Reynolds v. Army & Air Force Exch. Serv.*, 846 F.2d 746, 748 (Fed. Cir. 1988). Under RCFC 12(b)(1), a defendant can seek dismissal for lack of subject matter jurisdiction by making a facial attack, in which the allegations of the complaint are taken as true. *Hughes v. Rowe*, 449 U.S. 5, 10 (1980) (citation omitted); *Cedars- Sinai Med. Ctr. v. Watkins*, 11 F.3d 1573, 1584 (Fed. Cir. 1993). However, with respect to subject matter jurisdiction, a court does not need to presume the truthfulness of the plaintiff's allegations. *Reynolds*, 846 F.2d at 747; *Cedars-Sinai*, 11 F.3d at 1583. Rather, the court may consider matters outside of the plaintiff's complaint in assessing its jurisdiction, without converting the motion into one for summary judgment. *See Engage Learning, Inc. v.*

*Salazar*, 660 F.3d 1346, 1355 (Fed. Cir. 2011) (citing *Arbaugh v. Y&H Corp*., 546 U.S. 500, 514 (2006)).

**II. Fifth Amendment Takings**

The plaintiff in an inverse condemnation action bears the burden of pleading the facts that ultimately bear on whether a taking has occurred. *Ridge Line, Inc. v. United States*, 346 F.3d 1346, 1355 (Fed. Cir. 2003) (citation omitted). First, Plaintiffs must identify the precise government action that is the basis of the claim. *Acceptance Ins. Cos. v. United States*, 583 F.3d 849, 855 (Fed. Cir. 2009) (an alleged taking "consisting of several distinct [government] actions viewed in concert" is too broad of a characterization because it does not pinpoint what step in the order of events constituted conduct that would be a taking). Once plaintiffs identify the precise government action, they "must establish that treatment under takings law, as opposed to tort law, is appropriate under the circumstances." *Ridge Line,* 346 F.3d at 1355 (citation omitted). *See also Acceptance*, 583 F.3d at 855. That is because "not every 'invasion' of private property resulting from government activity amounts to an appropriation," and "[o]nly under limited circumstances may the property-owner be compensated for a taking." *Ridge Line*, 346 F.3d at 1355; *Nicholson v. United States*, 77 Fed. Cl. 605, 616 (2007).

**ARGUMENT**

**I. Plaintiffs Have Failed to State a Claim Upon Which Relief Can Be Granted.**

A. Sovereign Actions Undertaken to Minimize or Mitigate an Inevitable Public Harm Do Not Constitute a Taking of Private Property.

Plaintiffs do not present a cognizable taking claim because the Corps' actions were an exercise of governmental power to prevent loss of life and mitigate inevitable damages to private property as part of the emergency response to Hurricane Harvey, an extraordinary natural disaster. The Supreme Court has long maintained a distinction between the exercise of police

power and the taking of private property for public use. All property rights are held subject to "a fair exercise" of the police power. *Chi. & Alton R.R. v. Tranbarger*, 238 U.S. 67, 77 (1915). Consequently, even the destruction or seizure of property is not generally viewed as a compensable taking so long as the government is acting to protect public health or safety. *See, e.g., Mugler v. Kansas,* 123 U.S. 623 (1887). And where, as here, the government action is part of an effort to reduce or mitigate inevitable harms to the public, no viable taking claim exists. *See, e.g., Miller*, 276 U.S. at 279. *See also Bowditch v. City of Boston,* 101 U.S. 16, 18-19 (1879) (government not liable for a taking where firefighters destroyed a home to arrest the spread of fire in the protection of other private properties). The application of that well-established principle of takings law is particularly appropriate where, as here, the government is confronted with an extraordinary natural event like Hurricane Harvey.

A long line of cases holds that no taking occurs when the government's action incidentally results in damage to private property as the government seeks to protect the public from harm. The seminal case in this line of authority is *Miller*, where the Supreme Court affirmed a Virginia Supreme Court decision upholding the destruction of a large number of ornamental red cedar trees, without compensation, in accordance with a state law designed to protect neighboring apple orchards. 276 U.S. at 277.

In *Miller*, legislation gave the Virginia State Entomologist the authority and discretion to order the destruction of red cedars found growing within a two-mile radius of any apple orchards because of the destructive nature of a fungus that spreads between red cedars and apple trees. *Id.* This order necessitated damage to private property where red cedar trees were growing. But failure to issue such an order would result in damage to apple orchards. The state had to decide how to address an inevitable harm to private property—the loss of red cedars or damages to the

local apple industry. In finding no compensable taking, the Supreme Court recognized the unenviable dilemma governments face when they must choose between the preservation of two types of property in dangerous proximity, stating:

> It would have been none the less a choice if, instead of enacting the present statute, the state, by doing nothing, had permitted serious injury to the apple orchards within its borders to go on unchecked. When forced to such a choice the state does not exceed its constitutional powers by deciding upon the destruction of one class of property in order to save another which, in the judgment of the legislature, is of greater value to the public.

*Miller*, 276 U.S. at 279.

In a recent case involving "the most traditional function of the police power: entering property to arrest" a criminal suspect, this Court held that there was no taking of real property. *Bachmann v. United States*, 134 Fed. Cl. 694, 697 (2017). "When private property is damaged incident to the exercise of the police power, such damage is not a taking for the public use, because the property has not been altered or turned over for public benefit. Instead, both the owner of the property and the public can be said to be benefited by the enforcement of criminal laws and cessation of the criminal activity." *Id.* at 696 (citing *Nat'l Bd. of YMCA v. United States*, 395 U.S. 85, 92–93 (1969) ("temporary, unplanned occupation" of building by troops under exigent circumstances is not a taking). *Bachmann* confirms the continuing vitality of the principle that the Fifth Amendment does not invariably require compensation for government-caused damage to private property.

The *Miller* doctrine plainly applies here. Plaintiffs allege that their property rights were taken as the result of the Corps' operation of the Addicks and Barker dams before, during, and after Hurricane Harvey. Compl. ¶¶ 59-66. Hurricane Harvey was a record-setting storm—unprecedented not only for Houston, but in the entire history of the United States—in which severe flooding was inevitable. Plaintiffs fail to identify in their complaint an approach that the

Corps could have adopted to protect all privately-owned property—above and below the dams—from flooding. Nor do Plaintiffs allege that such widespread protection was possible. Instead, Plaintiffs necessarily maintain that the Corps is liable for a taking, even when it faced only "two options," to release floodwaters on downstream properties or to risk dam failure and "flooding other communities." Compl. ¶ 64. At the same time, upstream landowners are asserting a version of the same claim in the opposite direction—they assert that the government should have prevented too much water from being impounded by the reservoirs. *See* Master Am. Complaint for Upstream Plaintiffs ¶¶ 1, 9, No. 17-9001L (Fed. Cl.), ECF No. 18. Those conflicting claims vividly illustrate that Hurricane Harvey created a no-win situation for the Corps akin to the one confronting the State of Virginia in *Miller*. Like Virginia, "the Corps was left with two options: release water from the dams and flood the downstream properties, or risk exceeding the reservoir system's capacity and flooding other communities[,]" where both actions would inevitably result in some harm to some property owners. Compl. ¶ 64. Caught between a rock and a hard place, the Corps followed procedures aimed at preserving the dams and mitigating flood damages. That is not a taking. The Fifth Amendment has not created a constitutional flood insurance policy. No taking arises where, as here, the United States is simply acting to mitigate or minimize the inevitable harm to the public caused by an extraordinary Act of God.

The Texas Supreme Court, addressing what it likewise perceived to be a no-win scenario in a taking case that involved flooding in Harris County, has held that this is exactly the scenario in which a taking does <u>not</u> occur:

> [T]he homeowners' theory of takings would place governments in an unending dilemma of requiring extreme flood-control measures and facing a regulatory takings claim from the owners directly subjected to such measures, or requiring less extensive measures and facing a takings claim when downstream property owners experience flooding.

*Harris Cty. Flood Control Dist. v. Kerr*, 499 S.W.3d 793, 810 (Tex. 2016). The Court cautioned against reducing "flood control decisions . . . to picking your plaintiff rather than responsible flood control management." *Id.* Like the Texas Supreme Court in *Kerr*, this Court should "decline to extend takings liability vastly beyond the extant jurisprudence, in a manner that makes the government an insurer for all manner of natural disaster." *Id.*

Flooding from Hurricane Harvey was inevitable given the amount, duration and location of rainfall. Plaintiffs' claim of a taking must fail in this circumstance where the Corps acted to protect the general public during the emergency of a hurricane.

B. Under Texas Law and the Flood Control Act, Plaintiffs Do Not Possess the Property Interest Purportedly Taken.

The plaintiff in any Fifth Amendment taking action must establish, as a threshold matter, that they possess the property right purportedly taken. *See, e.g., Colvin Cattle Co. v. United States,* 468 F.3d 803, 806 (Fed. Cir. 2006). As the Federal Circuit has explained, the first step is for the Court to determine "whether the plaintiff possesses a valid interest in the property affected by the governmental action, *i.e.*, whether the plaintiff possessed [the pertinent] 'stick in the bundle of property rights.'" *Boise Cascade Corp. v. United States*, 296 F.3d 1339, 1343 (Fed. Cir. 2002) (quoting *Karuk Tribe of Cal. v. Ammon*, 209 F.3d 1366, 1374 (Fed. Cir. 2000)). Plaintiffs here do not possess the "stick" that was purportedly taken from their bundle of real property rights. The convergence of state law, longstanding federal law, and inherent limitations on the United States' obligation to protect all private property in emergency situations cabin a property owner's right to compensation when flooded by an act of God.

Plaintiffs allege a deprivation of "real and personal property interests," including the "use, occupancy, and enjoyment" of their property and a "temporary and/or permanent" flowage

easement. Compl. ¶¶ 105, 106, 109, 111, 112, 117. As a prerequisite to their taking claims, Plaintiffs must therefore establish that they have a right to property free of floodwaters resulting from a catastrophic hurricane like Harvey. They cannot do so because their rights were constrained by inherent limitations in use, because their property rights are limited by the government's exercise of the police power during an emergency under Texas law. Simply put, Plaintiffs cannot show they have a protected property right under Texas law to avoid releases of water from existing dams.

The Flood Control Act, which Congress enacted both before the dams were constructed and before Plaintiffs acquired their real property, is likewise fatal to their claim. Plaintiffs do not possess a protected property right at odds with this unambiguous background principle, which provides that no liability "of any kind" shall be imposed "upon the United States for any damage from or by floods or flood waters at any place." 33 U.S.C. § 702c. For these reasons, Plaintiffs fail to state a claim for relief under the Fifth Amendment.

#### ***1. Background Principles of Property Law Limit Cognizable Property Rights.***

The Constitution itself does not create or define property rights. Consequently, courts look to "background principles" derived from "an independent source such as state, federal, or common law" to determine whether a plaintiff has a cognizable property interest. *Maritrans, Inc. v. United States*, 342 F.3d 1344, 1352 (Fed. Cir. 2003) (citing *Lucas v. S.C. Coastal Council*, 505 U.S. 1003, 1030 (1992)); *Bd. of Regents v. Roth*, 408 U.S. 564, 578 (1972); *see also Ridge Line*, 346 F.3d at 1357 (assessing existence vel non of property interest according to West Virginia reasonable use law). Indeed, there is no taking if common law nuisance and property principles prohibit the desired land use or place an existing restriction on the property right claimed. *Lucas*, 505 U.S. at 1029.

### *2. Texas Law Recognizes No Right to Use and Enjoyment of Their Property Free From an Act of God.*

Texas law affords Plaintiffs no right to keep floodwaters from their properties, and no guarantee to the free use and enjoyment of their property during and after a Category 4 hurricane or "Act of God." *See Benavides v. Gonzalez*, 396 S.W.2d 512, 514 (Tex. App. 1965) (finding that "[u]nprecedented rainfall or Act of God is uniformly recognized" as a defense for allegedly unlawful diversions of water); *Ford Motor Co. v. Dallas Power & Light Co.*, 499 F.2d 400, 413 (5th Cir. 1974) (noting that a reservoir operator "did not create the flood" that caused the damage, and finding liability only for a failure to warn downstream owners). *Benavides* and other Texas authorities recognizing no liability based on flooding prompted by extreme precipitation or rainfall evidence no state recognition of their rights to keep property free from government-released floodwaters during and after a hurricane. *Id.*; *E.g. Sabine River Auth. of Texas v. Hughes*, 92 S.W.3d 640, 642 (Tex. App. 2002) (finding no intentional act of the government from extreme precipitation); *Wickham v. San Jacinto River Auth.*, 979 S.W.2d 876, 880-81 (Tex. App. 1998) (describing an allegation of flooding based on a rainfall event exceeding the 100-year frequency) (citing *DuPuy v. City of Waco*, 396 S.W.2d 103, 108-09 (Tex. 1965)). With respect to the alleged physical invasion, Plaintiffs suggest that their property was occupied by floodwaters only from August 28, 2017 to no later than September 9, 2017.[15] Compl. ¶¶ 6-46. Plaintiffs concede that over a five-day period, "approximately 50 inches of rain fell on Houston," that the Corps "feared it would lose its ability to control the water within the two reservoirs," and that there was a "risk [of] exceeding the reservoir system's capacity . . . ." Compl. ¶¶ 60, 62, 64. Plaintiffs must do more than assert the legal conclusion that they have a

[15] Plaintiffs allege various dates when floodwaters left the properties.

protected property right. They must show that the alleged property right has been recognized in circumstances similar to those presented here, a devastating natural disaster. *See e.g.*, *Severance v. Patterson*, 370 S.W.3d 705, 709-10 (Tex. 2012) (describing several limitations on property rights including the exercise of the police power). Plaintiffs cannot demonstrate a cognizable right to keep floodwaters from their properties given excessive record precipitation.

Plaintiffs also allege the Corps' release of Hurricane Harvey floodwaters constituted an interference with their rights to use and enjoy their property. Compl. ¶ 112. But, here again, Plaintiffs have no property right to free use and enjoyment of property during and after flooding prompted by a hurricane. This limitation on property rights is reflected in cases interpreting the Texas Constitution to recognize a taking only for a "physical appropriation or invasion," or "*unreasonable* interference with a landowner's right to use and enjoy the property." *Wickham*, 979 S.W.2d at 880 (emphasis added). The United States' alleged interference with a claimed right of use and enjoyment is only cognizable if unreasonable. *E.g. Strother v. City of Rockwall*, 358 S.W.3d 462, 472 (Tex. App. 2012). Plaintiffs do not plead, nor do the facts show that any interference with Plaintiffs' rights of enjoyment during a hurricane are unreasonable. Plaintiffs cannot show any protected property right in the free use and enjoyment of their property during a Category 4 hurricane and flooding that resulted therefrom. Absent such a cognizable property interest, Plaintiffs cannot state a viable claim for relief here.

### 3. *Texas Law Recognizes No Property Right to Protect Property From Invasions Caused by Pre-Existing Dams and Operations Thereof.*

Even if Plaintiffs were able to demonstrate a property right in keeping their properties free from emergency flood releases necessitated by a catastrophic hurricane, they cannot show that such right exists for any landowner who acquired property after the construction of the dams in the 1940s. Plaintiffs have identified no such claimant and indeed allege acquisitions of

properties downstream of the dams as recently as 2017—nearly seventy years after the last dam was completed. Compl. ¶ 26. Plaintiffs do not allege that the Corps changed operational protocol such that dam releases during Hurricane Harvey were any different than procedure dictated when they acquired their land. Thus, their property rights are constrained by water rights of dominant pre-existing estates such as that of the United States.

Background principles of state law limit an owner's rights to claims involving new construction or a new pattern of government operations. *See, e.g. Hansen v. United States*, 65 Fed. Cl. 76, 123-24 (2005) (analyzing what water rights had vested under South Dakota law). In *City of Tyler v. Likes*, the Texas Supreme Court rejected a taking and nuisance claim finding that there was no governmental activity that had increased the amount of water in the watershed *after* the culvert system was installed, more than ten years before the plaintiffs had acquired their home. 962 S.W.2d 489, 505 (1997). By contrast, in *Brazos River Authority v. City of Graham*, the Court found a taking where the property at issue was constructed *before* the dam at issue. 354 S.W.2d 99, 104 (1961) (describing how the water disposal plan was constructed before the dam and lake came into existence), *holding modified by Gilbert Wheeler, Inc. v. Enbridge Pipelines (E. Texas), L.P.*, 449 S.W.3d 474 (Tex. 2014) (finding no taking because no recurrent flooding). These authorities demonstrate that Plaintiffs cannot claim a taking based on the established operation of the dams, which long predate by decades the acquisition of their properties.

Plaintiffs also cannot base a claim on continued operation of the dams. A public entity's continued operation of a public program, or its alleged failure to implement corrective measures, does not encroach upon a protected property interest. *AN Collision Ctr. of Addison, Inc. v. Town of Addison*, 310 S.W.3d 191, 195-96 (Tex. App. 2010). Plaintiffs possess no right to be free

from invasions from the operation of projects whose construction and operations pre-dated the acquisition of their properties.[16] *See Thomas v. Bunch*, 41 S.W.2d 359, 361 (Tex. App. 1931), *aff'd*, 49 S.W.2d 421 (Tex. 1932) (holding that a landowner erecting a dam to protect land acquired a vested right to maintain dam as originally constructed); *see also City of Dallas v. Winans*, 262 S.W.2d 256, 258 (Tex. App. 1953) (finding no liability where municipality's operation had not changed, and noting that "if a cause of action ever existed, it was in favor of some remote predecessor in title, not appellee."); *Meuth v. City of Seguin*, No. 04–16–00183–CV, 2017 WL 603646 , at *3 (Tex. App. Feb. 15, 2017) (finding no liability where municipality continued to operate drainage culvert that was built prior to plaintiff's acquisition of property). Because Plaintiffs allege no new or changed operation of the dams after their acquisition, they possess no cognizable property right that could be taken under Texas law, and their claims should therefore be dismissed. *Cf. Brinston v. Koppers Indus., Inc.*, 538 F. Supp. 2d 969, 977 (W.D. Tex. 2008) (rejecting permanent nuisance claim because the plaintiffs did not own the property when the alleged nuisance originally commenced).[17]

Other cases suggest that a new government action could, in theory, constitute a taking, but the use of an existing structure could not. *E.g. Strother*, 358 S.W.3d at 471 (noting the city had not "created any physical structure"). *But cf. Gainesville, H. & W.R. Co. v. Hall*, 14 S.W.

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[16] The concept of a subsequent purchaser having no property right to be free from diversions from an existing structure is reflected also within the requirement that Plaintiffs demonstrate that their reasonable investment-backed expectations have been frustrated by the government activity. *See Ark. Game & Fish Comm'n v. United States*, 568 U.S. 23, 38-39 (2012). Here, Plaintiffs do not allege any facts that the Corps has altered long established operations of the dams.

[17] Nuisance law typically provides instructive guidance on what property rights are recognized by state law because taking law was not intended to make the state liable in circumstances where a private owner would not be liable based on nuisance or other law. *See Gainesville, H. & W.R. Co. v. Hall*, 14 S.W. 259, 260 (Tex. 1890).

259, 261 (Tex. 1890) (awarding damages based on operation of a subsequently-constructed railroad). In the instant litigation, Plaintiffs allege injury and damage to their properties, the loss of the right to possession, and the loss of rights to use and enjoy their properties. Compl. ¶ 84. Other than these generally articulated rights, Plaintiffs allege no specific right to keep their properties free from emergency floodwater released upstream. Plaintiffs do not allege that Addicks and Barker were constructed after they acquired their properties. Nor do they allege that the Corps has somehow altered its operation plans after plaintiffs acquired their properties. Rather, all Plaintiffs appear to have purchased their properties, with constructive knowledge that they are downstream of a dam, so their property rights are inherently constrained by the pre-existing dam. The Corps' continued operation of the dams, did not, therefore interfere with any of Plaintiffs' cognizable property interests.

#### *4. The Flood Control Act Is a Longstanding Background Principle That Shapes Plaintiffs' Property Rights.*

Even apart from these principles of Texas law, which are independently sufficient to foreclose Plaintiffs' claims, Plaintiffs' property rights are further shaped by background principles established in the Flood Control Act. The Act addresses rights and expectations with respect to floods and floodwaters, and which predates both the dams and Plaintiffs' ownership of their property. The Flood Control Act is clear and unequivocal: "[n]o liability of any kind shall attach to or rest upon the United States for any damage from or by floods or flood waters at any place."[18] 33 U.S.C. § 702c. The plain language and longstanding existence of Section 702c

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[18] The broad and seemingly unequivocal language of Section 702c raises the question whether the statute has withdrawn, in relevant respects, the waiver of sovereign immunity that underlies this Court's subject matter jurisdiction. *See United States v. James*, 478 U.S. 597, 606-08 (1986) (opining that Section 702c "clearly sought to ensure beyond doubt that sovereign immunity would protect the Government from 'any' liability associated with flood control"), *abrogated by Cent. Green*, 531 U.S. 425 (2001). The Federal Circuit has found no "unambiguous evidence in

defeat Plaintiffs' claims. *Cf. B. Amusement Co. v. United States*, 148 Ct. Cl. 337, 342 (1960) (finding that even if the policy of non-liability in Section 702c is based on public policy and not sovereign immunity, it is at any rate a withdrawal of consent to be sued).

In circumstances where the federal government has long exercised dominant control in an industry, private property rights are frequently limited by government action or regulation. *See Air Pegasus, Inc. Co. v. United States*, 424 F.3d 1206, 1217-18 (Fed. Cir. 2005) (discussing public transit regulations and finding no property right in navigable airspace); *United States v. Twin City Power Co.*, 350 U.S. 222, 225-28 (1956) (holding that riparian landowners took their interest in a stream subject to the government's dominant navigational servitude). Furthermore, where the federal government's regulatory authority can change or restrict the scope of a claimed property right, no private property right exists. *E.g.*, *Am. Pelagic Fishing Co. v. United States*, 379 F.3d 1363, 1374 (Fed. Cir. 2004). The federal government has exercised authority in the area of flood risk reduction since the nineteenth century. *See* Rivers and Harbor Act of 1888, codified at 33 U.S.C. § 601. This long-standing exercise of federal authority shapes what property rights are cognizable.

The Flood Control Act was enacted in 1928. *Nat'l Mfg. Co. v. United States*, 210 F.2d 263, 270 (1954). It had been in place nearly twenty years before the Addicks and Barker dams were complete. The dams were constructed pursuant to Flood Control Act authority and against

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the text or legislative history of § 702c that Congress had withdrawn the Tucker Act grant of jurisdiction." *California v. United States*, 271 F.3d 1377, 1383 (Fed. Cir. 2001) (quoting *Ruckelshaus v. Monsanto Co.*, 467 U.S. 986, 1017 (1984)); *see also id.* (finding the legislative history discussed in *James* to be "an insufficient basis . . . upon which to presume an implied partial repeal of the Tucker Act"). *But see Horne v. Dep't of Agric.*, 569 U.S. 513, 527 (2013) (enunciating a different approach for "determin[ing] whether a statutory scheme displaces Tucker Act jurisdiction"). The United States does not seek dismissal of Plaintiffs' claims on this ground at this time. We identify the issue because it goes to this Court's subject matter jurisdiction.

the backdrop of Section 702c.[19] It was another thirty years (or more) before, according to the Complaint, Plaintiffs acquired their property. *See* Compl. ¶¶ 6-46. They did so against the backdrop of public facilities that had at that time been operated for generations, providing both benefits and burdens to the local community, and against the backdrop of an unequivocal provision that barred the recovery of damages relating to floods and floodwaters.[20] In other words, Section 702c constitutes an established background principle that has been in place for nearly 100 years.

Plaintiffs do not allege that the Addicks and Barker dams were constructed after they acquired their properties. Nor do they allege that after acquisition of their properties the Corps altered its operations to their detriment. Instead, Plaintiffs seek compensation for damages resulting from the floods or floodwaters of Hurricane Harvey. *See* Compl. ¶¶ 71-75. The character of the waters that allegedly caused the claimed damage and the purposes behind their release are determinative. *Cent. Green v. United States,* 531 U.S. 425, 436 (2001). A release of water from a flood control project that has reached flood stage, or of waters that such project cannot control, during a catastrophic storm are without question floodwaters within the meaning of the Flood Control Act. *See id.* at 436-37. And because Section 702c constitutes a background principle, it also acts as a bar to liability. Plaintiffs' claims should therefore be dismissed.

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[19] The Addicks and Barker dams were authorized under the Rivers and Harbors Act of 1938, which resulted from the 1936 Flood Control Act, and which retained the immunity provision of the 1928 Flood Control Act. Pub. L. No. 75-685, 52 Stat. 802 (1938)

[20] The Corps alone is responsible for the operation of over 500 dam projects authorized by various Flood Control Acts and other statutes, including more than 300 of which that have flood-control as one of the authorized purposes. 33 C.F.R. § 222.5 App. E. Other government agencies operate additional federal projects, some of which have flood-control purposes as well.

### C. Plaintiffs' Alleged Government Action, Taken as a Whole, Does Not Effect a Taking.

Plaintiffs' alleged government action, as described in the Complaint and accepted as true, does not constitute a taking. Plaintiffs claim that "[a]s a direct, natural, and probable result of the Corps' intentional decisions and conduct described above, water physically invaded Plaintiffs' real and personal property." Compl. ¶ 105. Plaintiffs focus on the Corps' response to unexpected rise of storm water in the reservoirs, claiming that the Corps took their property when it opened the Addicks and Barker floodgates on August 27, 2017, Compl. ¶¶ 65-66, 105-106. But Plaintiffs readily concede that the Corps could not have opened the gates had it not closed them two days earlier. *Id.* ¶ 59. The opening of the floodgates was not a discrete action; it was inextricably linked with the Corps' overall storm response to *minimize* downstream flooding by first closing the floodgates. Had the Corps done nothing, the floodgates would have remained open throughout the entire storm.

Plaintiffs improperly segregate the Corps' August 27, 2017 re-opening of the floodgates from the Corps' closure of the floodgates two days prior; these two actions were part of one integrated response to Hurricane Harvey. Because the Corps could not have released water had it not earlier closed the floodgates, the two acts must be viewed in tandem. Plaintiffs cannot "cherry-pick" government action, isolating the act complained of from the entirety of the government course of conduct. *See Cary v. United States*, 552 F.3d 1373, 1377 n.* (Fed. Cir. 2009) (criticizing landowners for cherry-picking the parts of the Forest Service's fire policy that allegedly harmed them, with no acknowledgment that much of the Forest Service policy reduced their risk of wildfire); *see also John B. Hardwicke Co. v. United States*, 467 F.2d 488, 491 (Ct. Cl. 1972) (plaintiffs could not have "reasonably supposed that [their land] could benefit from the

impoundment of water at [the primary dam in question], yet be free of the disadvantages that might arise from the diversion dam, when built and in use.”).

The government action Plaintiffs have conclusory asserted does not correspond with the factual allegations that they have alleged and should not be accorded deference. *Iqbal*, 556 U.S. at 678. The Court is obligated to accept only factual allegations as true. Applying this rubric, it becomes apparent that the government action at issue is the United States’ storm response, which includes both the Corps’ closing and opening of the floodgates. Thus, Plaintiffs have failed to plead facts sufficient to allege an appropriately-defined government action was the “but-for” cause of the flooding of their properties.[21] Plaintiffs are located immediately downstream of the dams and acknowledge that some of their homes are within the designated 100-year or 500-year floodplain. Compl. ¶¶ 6-46, 83. Plaintiffs have not alleged that, had the Corps done nothing and left the gates open on August 25, 2017, that their property would not have flooded. Indeed, it is highly likely that Plaintiffs’ properties would have flooded had the Corps done nothing. Because Plaintiffs fail to incorporate all of the government action and do not allege that flooding was either more severe or only occurred because of the government action, they cannot state a claim.

D. <u>Plaintiffs’ Claim That the United States Has Taken Unidentified “Other Property Interests” Is Legally Deficient.</u>

For a complaint to state a valid claim under this Court’s Rules, a plaintiff must include “a short and plain statement of the claim showing that the pleader is entitled to relief.” RCFC 8(a)(2). Moreover, for a Fifth Amendment taking claim, a plaintiff must plead with particularity

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[21] The Court of Federal Claims has acknowledged that plaintiffs’ burden under the *Ridge Line* “direct, natural, or probable result” requirement, *Ridge Line*, 346 F.3d at 1355, exceeds the threshold of demonstrating traditional but-for causation. In *Moden v. United States*, the Court adopted the position advocated by the government, which it described thus: “Simplified somewhat, the government’s interpretation requires that the injury was the likely result of the act, whereas the Modens’ interpretation requires only that the act was the likely cause of the injury.” *Moden*, 404 F.3d 1335, 1343 (Fed. Cir. 2005).

the "specific property interest" allegedly taken by the United States. *See* RCFC 9(i). This pleading requirement applies equally to alleged takings of real, personal, intangible, or other property. The failure to meet these pleading requirements is grounds for dismissal. *See Bell Atl. Corp. v. Twombly*, 550 U.S. 544, 570 (2007) (holding that plaintiff must plead "enough facts to state a claim to relief that is plausible on its face," which "requires more than labels and conclusions, and a formulaic recitation of the elements of a cause of action. . .").

Here, Plaintiffs offer general allegations about the purported taking of unspecified property, without identifying the specific property purportedly taken. Paragraph 103 of the Complaint states generally that "[p]laintiffs have legally cognizable property interests in the real and personal property located at their residences, businesses, and other properties located near or downstream from the Addicks and Barker Reservoirs." However, paragraphs 6 through 46, which set forth the claims of each individual Plaintiff, identify no specific personal or other property that the Plaintiff alleges to have been taken by the United States. *Id.* ¶¶ 6-46. A catchall allegation in paragraph 69 mentions only "belongings." *Id.* ¶ 69. Rule 9(i) does not allow a plaintiff to seek compensation for a taking without specifically identifying the property and property interest allegedly taken. The identification of particular property is essential because each property interest purportedly taken—real, personal or otherwise—must be analyzed independently and just compensation is available only for the fair market value of a taking of property that is pled and proved, not for consequential damages. *Indep. Park Apartments v. United States*, 465 F.3d 1308, 1311 (Fed. Cir. 2006) (citations omitted).

Plaintiffs had the opportunity to cure these deficiencies after the United States explicitly identified them in its Motion for More Definite Statement, but Plaintiffs chose to reassert vague and legally insufficient allegations. Plaintiffs' failure to identify the specific personal property of

each Plaintiff violates RCFC 9(i) and prevents the United States from reasonably preparing a response and developing its defenses. The Court should dismiss Plaintiffs' claims for the taking of unidentified "personal property" for failure to state a claim upon which relief can be granted.

## II. Plaintiffs' Claims Should Be Dismissed For Lack of Subject Matter Jurisdiction Because The Flooding Here Is at Most a Tort; It Is Not a Compensable Taking.

### A. Plaintiffs Have the Burden To Prove Treatment as a Taking Is Appropriate Based on Facts Alleged.

The plaintiff in an inverse condemnation action bears the burden of pleading and proving the facts that ultimately bear on jurisdiction. *Ridge Line*, 346 F.3d at 1355. This means that, among other things, the plaintiff "must establish that treatment under takings law, as opposed to tort law, is appropriate under the circumstances." *Id.* at 1355 (citation omitted); *Acceptance*, 583 F.3d at 855. It is well-established that "not every 'invasion' of private property resulting from government activity amounts to an appropriation," and "[o]nly under limited circumstances may the property-owner be compensated for a taking." *Ridge Line*, 346 F.3d at 1355; *Nicholson*, 77 Fed. Cl. at 616 (citation omitted). Whether a claim is a tort or a taking "requires consideration" of the government's action and whether that action was "sufficiently substantial to justify a takings remedy." *Ridge Line*, 346 F.3d at 1355. The plaintiff must show either that the government intended to take its property or that such an intent can fairly be deemed to exist because a taking is the "direct, natural, or probable result" of the government action. *Id.* (quoting *Columbia Basin Orchard v. United States*, 132 F. Supp. 707, 709 (Ct. Cl. 1955)). The interference must also be "substantial and frequent enough to rise to the level of a taking." *Id.* at 1357 (citation omitted). This tort-taking distinction is a threshold question because tort claims are not within the Court's jurisdiction. *Id.* at 1355; 28 U.S.C. § 1491(a)(1).

Relatedly, long-standing precedent requires that the plaintiff establish that the government act that allegedly caused the taking was lawful and authorized, and either

"appropriate[d] a benefit to the government at the expense of the property owner, or at least preempt[ed] the owners['] right to enjoy his property for an extended period of time, rather than merely inflict an injury that reduces its value." *Ridge Line*, 346 F.3d at 1356 (citation omitted).

Plaintiffs' claims should be dismissed because they have neither pled sufficient facts, nor can they prove, that their claims should be treated as takings, rather than torts. Plaintiffs offer only cursory and speculative allegations about the supposed permanence of the alleged taking. *See e.g.* Compl. ¶¶ 88, 117 (alleging that "future flooding will be more likely[,]" and that the Corps hasn't eliminated "the risk of future flooding.") Plaintiffs acknowledge that Hurricane Harvey was an extraordinary storm. Floodwaters receded soon after the hurricane ended. Plaintiffs do not allege that the Corps' operation of the Addicks and Barker dams flooded their properties before or since the hurricane. Put simply, according to their own allegations, flooding has not been permanent, frequent, recurrent, or even likely to recur in the future. Plaintiffs have not even adequately pled facts to show the government—as opposed to the hurricane—either caused the flooding in question, or that an identified government action set in motion a chain of events of which the flooding was a natural consequence. *Cf. Nicholson*, 77 Fed. Cl. at 618 (finding that Hurricane Katrina, not the installation of floodwalls, caused flooding); *Bartz v. United States*, 633 F.2d 571, 593 (Ct. Cl. 1980) (finding that "excessive precipitation," not dam releases caused flooding).

Moreover, a one-time hurricane-induced flood stemming from a 1000-year storm—rather than "government-induced" flooding from routine operations—is not "substantial and frequent enough to rise to the level of a taking." *Ridge Line*, 346 F.3d at 1357 (citation omitted). Numerous cases establish that even infrequently-recurring floods, let alone one-time floods, do

not constitute a taking.[22] This case is fundamentally distinguishable, even at the pleadings stage, from *Arkansas Game & Fish*. In that case, the flooding resulted from the routine operation of a government dam under "normal" circumstances not during an emergency resulting from a hurricane and an historic rain event. And the flooding, while temporary, recurred each year for several years. 568 U.S. 23. Here, Plaintiffs fail to plead facts plausibly establishing the severe and frequent invasion of a protected property right necessary to state a taking claim under controlling legal authority, including *Arkansas Game & Fish*. Plaintiffs' claims arise, if at all, in tort. Consequently, their claims should be dismissed.

B. <u>Plaintiffs' Conclusory Allegations Are Not Entitled to a Presumption of Correctness.</u>

Plaintiffs' conclusory allegations do not enjoy a presumption of correctness. Even at the motion to dismiss stage, Plaintiffs bear the burden of "alleg[ing] facts sufficient to establish the court's subject matter jurisdiction."[23] *The George Family Trust ex rel. George v. United States*, 91 Fed. Cl. 177, 189 (2009) (citing *Renne v. Geary*, 501 U.S. 312, 316 (1991)) (granting motion to dismiss in part and denying it in part, in government-induced flooding case). "Once the court's subject matter jurisdiction is [called] into question, . . . [the plaintiff] bears the

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[22] Texas cases establish that, although recurrence is not an absolute requirement to prove a taking, "recurrence is a probative factor in determining the extent of the taking and whether it is necessarily incident to authorized government activity, and therefore substantially certain to occur." *City of El Paso v. Mazie's L.P.*, 408 S.W.3d 13, 24 (Tex. App. 2012) (quoting *Tarrant Reg'l Water Dist. v. Gragg*, 151 S.W. 3d 546, 555 (Tex. 2004)).

[23] The Federal Circuit has treated a motion to dismiss a flooding-related takings case based on the tort-taking distinction as a motion for failure to state a claim under RCFC 12(b)(6), converted to a motion for summary judgment under RCFC 56, rather than a dismissal for lack of subject matter jurisdiction under RCFC 12(b)(1). *See Moden*, 404 F.3d at 1339-42. However described, the *Ridge Line* elements clearly are subject to the pleading requirements of *Iqbal* and *Twombly*. *See George Family Trust*, 91 Fed. Cl. at 201 (citing *Iqbal*, 556 U.S. 662 and *Twombly*, 550 U.S. 544).

burden of establishing subject matter jurisdiction by a preponderance of the evidence." *Id.* (additional citations omitted). When a motion to dismiss "controverts the plaintiff's jurisdictional allegations and challenges the factual basis of the court's jurisdiction, the plaintiff must demonstrate facts sufficient to support jurisdiction," and the Court is not limited to considering the allegations of the complaint. *Id.* at 190 (citing *Cedars-Sinai Med. Ctr. v. Watkins*, 11 F.3d 1573, 1583-84 (Fed. Cir. 1993)).

Plaintiffs' master complaint fails to allege facts that, if proven, would demonstrate that the government caused flooding other than during Hurricane Harvey itself, and their bare recitation of various legal conclusions is insufficient to meet their burden to establish jurisdiction. "[T]he tenet that a court must accept as true all of the allegations contained in a complaint is inapplicable to legal conclusions. Threadbare recitals of the elements of a cause of action, supported by mere conclusory statements, do not suffice." *Iqbal*, 556 U.S. at 678 (citing *Twombly*, 550 U.S. at 555). "In keeping with these principles a court considering a motion to dismiss can choose to begin by identifying pleadings that, because they are no more than conclusions, are not entitled to the assumption of truth." *Id.* at 679.

Here, Plaintiffs' bare allegations that the United States has a "commitment to the intermittent, but recurring, flooding of Plaintiffs' properties should flood events that necessitate the reservoirs' release occur again" or that "[e]ach time an extreme flood event occurs . . . the downstream properties will again be flooded"," *see* Compl. ¶¶ 117, are not entitled to a presumption of truth and are legally insufficient. These very allegations acknowledge that the true catalyst for any hypothesized future flooding would be an "extreme flood event" or "flood events that *necessitate* the reservoirs' release." Compl. ¶ 117 (emphasis added). Plaintiffs' allegations, taken as true, still require a natural disaster-induced floods, for any government

action to cause of damage to downstream properties. And Plaintiffs do not allege, much less plead facts that plausibly establish, the supposed frequency of hypothetical future flooding. Plaintiffs offer no more than the allegation that floods occurred when Texas was struck by an extraordinary 1000-year storm. Similarly, the conclusory allegation that "the Corps' decisions have also altered the course of Buffalo Bayou in such a manner that future flooding will be more likely in areas not previously subject to flooding," Compl. ¶ 87, is insufficient. There is no factual basis or reasonable inference that the 2017 action complained of by Plaintiffs—the opening of the Addicks and Barker floodgates—alters the course of Buffalo Bayou.

C. Plaintiffs' Allegations Are Insufficient to Establish a Taking, Rather Than a Tort.

Although *Arkansas Game & Fish* addressed the legal standards applicable where a plaintiff alleges a temporary, but recurring, physical taking, it did not disrupt the general *Ridge Line* test, and cited the decision approvingly. *Ark. Game & Fish*, 568 U.S. at 38. As the Supreme Court explained, it ruled, "simply and only, that government-induced flooding temporary in duration gains no automatic exemption from Takings Clause inspection." *Id.* The Court thus rejected a per se rule that a flood must be permanent or inevitably recurring for it to constitute a taking, and made clear that a taking could potentially be shown when "government-induced flood invasions, although repetitive, are temporary."[24] *Id.* at 26.

The tort-taking test in *Ridge Line* has two parts, both of which must be satisfied to demonstrate the Court has jurisdiction over a taking claim, and that the allegations do not instead sound in tort. A taking cannot occur through negligence or inadvertence. Consequently, under

[24] Significantly, the "government-induced flood invasions" in *Arkansas Game & Fish* resulted from purposeful releases from the dam where the Corps deviated from the existing operations manual, made recurrent and repeated over many years, and where the releases were scheduled and intentional. *Id.* The one-time flooding here was none of these things; the government acted in an emergency created by a hurricane, and Plaintiffs do not allege facts plausibly establishing when, if ever, flooding of their property will occur again.

*Ridge Line*'s first part, a plaintiff must establish that the government's action intended to invade and take a property interest or that the taking of property was so certain in the ordinary course that such intent should be deemed to exist. 346 F.3d at 1355-56. Additionally, under *Ridge Line*'s second part, a plaintiff must allege facts plausibly establishing that "the government's actions were sufficiently substantial to justify a takings remedy." *Id.* Both the "nature and magnitude of the government action must be considered." *Id. at* 1356. Importantly, the "government's interference with any property rights . . ." must be "substantial and frequent enough to rise to the level of a taking." *Id.* at 1357 (citation omitted). A single storm-induced flood is an "isolated invasion," and even "one or two floods" are unlikely to meet the standard of "substantial and frequent." *Id.* Isolated invasions contrast with "repeated invasions of the same type [that] have often been held to result in an involuntary servitude." *Id.* (quoting *Eyherabide v. United States*, 345 F.2d 565, 569 (Ct. Cl. 1965)). *See also Fromme v. United States*, 412 F.2d 1192, 1197 (Ct. Cl. 1969) (holding that a taking could not be found where flooding of land could "reasonably be expected to recur… once in every 15 years, on the average"); *N. Ctys. Hydro-Elect. Co. v. United States*, 151 F. Supp. 322, 323 (Ct. Cl. 1957) ("[t]wo floodings, one ten years after the pool behind the dam was completely full, and the other nineteen years after, do not constitute a taking…"); *accord Ark. Game & Fish*, 568 U.S. at 39 ("[W]hile a single act may not be enough, a continuance of them, in sufficient number and for a sufficient time may prove [a taking].") (quoting *Portsmouth Harbor*, 260 U.S. at 329-330 (finding that government acts occurring periodically over a period of decades may not be a taking, but instead "occasional torts" and remanding the case for consideration of that question)).

Plaintiffs likewise fail to plead facts sufficient to establish that any flooding has been recurrent or repeated. Only a handful of Plaintiffs allege prior-flooding on their properties, *see*

Compl. ¶¶ 6, 9, 34, 43, 83 (concerning only four of the properties), but, notably, Plaintiffs do *not* allege that any such previous flooding was in any way caused or connected to the Addicks and Barker reservoirs or to government action. Plaintiffs' unsupported and speculative allegation that Corps decisions have "altered the course of Buffalo Bayou in such a manner that future flooding will be more likely" and that the United States has "shown a commitment to the intermittent, but recurring, flooding of Plaintiffs' properties" is refuted by their own allegations, which identify no other instance in roughly 70 years of dam operation—a period during which other tropical storms and hurricanes hit the area—when flooding of their property could be attributable to the government.[25] Compl. ¶¶ 88, 117. It is also refuted by Plaintiffs' own concession that such flooding may only occur "should flood events . . . necessitate the reservoirs' release." *Id.* at ¶ 117. Neither the "apprehension of future flooding" nor the concern that some future government action may make flooding more likely suffice to state a taking claim. *Sponenbarger*, 308 U.S. at 267; *Danforth v. United States*, 308 US. 271, 286 (1939); *Stueve Bros. Farms, LLC v. United States*, 105 Fed. Cl. 760, 767–68 (2012), *aff'd*, 737 F.3d 750 (Fed. Cir. 2013) (finding that mere "apprehension of future flooding" does not impose a taking in the form of a flowage easement). Plaintiffs are unable to show that flooding is likely to recur because it was caused by an unpredictable and unforeseeable natural disaster, rather than as a result of purposeful government activity. The one-time flooding here as the result of an unprecedented hurricane is insufficient to state a taking claim under *Ridge Line*. *See, e.g.*

[25] Plaintiffs do not specify whether the Corps decisions they allege "altered the course of Buffalo Bayou" were the same actions—opening the gates—that they allege caused the flooding during Hurricane Harvey. Compl. ¶¶ 81, 87, 88. To the extent any of Plaintiffs' allegations are based on other unspecified Corps actions pursuant to the Buffalo Bayou and Tributaries Project that followed dam construction, such allegations took place decades ago and are barred by the six year statute of limitations applicable to claims under the Fifth Amendment. 28 U.S.C. § 2501.

*Nicholson*, 77 Fed. Cl. at 618 (rejecting taking claim based on Hurricane Katrina after rejecting the notion that the flooding was a "condition initially set in motion by the" government action as opposed to the hurricane).

## CONCLUSION

For these reasons, pursuant to RCFC 12(b)(1) and 12(b)(6), the United States respectfully requests that the Court dismiss the actions in the downstream sub-master docket.

February 20, 2018

Respectfully submitted,

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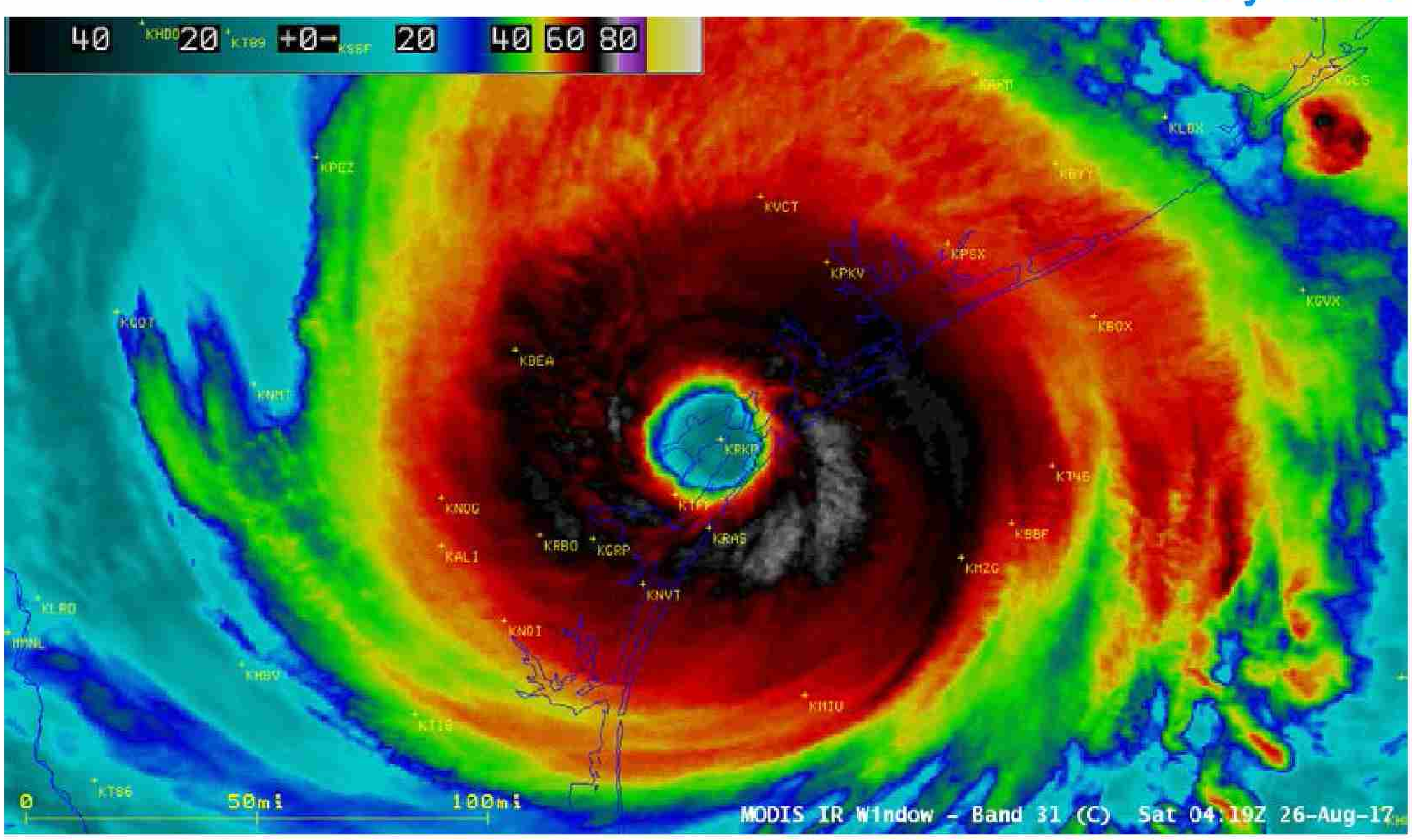
# NATIONAL HURRICANE CENTER TROPICAL CYCLONE REPORT

# HURRICANE HARVEY

## (AL092017)

## 17 August – 1 September 2017

Eric S. Blake and David A. Zelinsky
National Hurricane Center
23 January 2018




**NASA TERRA MODIS INFRARED IMAGE OF HARVEY AT 0419 UTC 26 AUGUST 2017 JUST AFTER LANDFALL AS A CATEGORY 4 HURRICANE IN TEXAS. IMAGE COURTESY OF UW/CIMSS.**

Harvey started as a typical weak August tropical storm that affected the Lesser Antilles and dissipated over the central Caribbean Sea. However, after re-forming over the Bay of Campeche, Harvey rapidly intensified into a category 4 hurricane (on the Saffir-Simpson Hurricane Wind Scale) before making landfall along the middle Texas coast. The storm then stalled, with its center over or near the Texas coast for four days, dropping historic amounts of rainfall of more than 60 inches over southeastern Texas. These rains caused catastrophic flooding, and Harvey is the second-most costly hurricane in U.S. history, after accounting for inflation, behind only Katrina (2005). At least 68 people died from the direct effects of the storm in Texas, the largest number of direct deaths from a tropical cyclone in that state since 1919.

# Hurricane Harvey

## 17 AUGUST – 1 SEPTEMBER 2017

## SYNOPTIC HISTORY

The wave that spawned Harvey moved off the west coast of Africa on 12 August with a large convective mass that had mostly dissipated by late the next day. Convection increased near the wave axis on 15 August, likely due to the passage of a convectively coupled Kelvin wave early that day (Fig. 1). A low pressure center formed early on 16 August, but easterly shear initially prevented any organization of the associated convection. The shear relaxed overnight, allowing deep convection to build near the center, and a tropical depression formed around 0600 UTC 17 August about 440 n mi east of Barbados. The depression became a tropical storm 12 h later. The "best track" chart of Harvey's path is given in Fig. 2, with the wind and pressure histories shown in Figs. 3 and 4, respectively. The best track positions and intensities are listed in Table 1[1].

Harvey moved quickly westward, south of a western Atlantic ridge, reaching an initial peak intensity of 40 kt early on 18 August. The storm's center passed over Barbados at 1000 UTC that day and St. Vincent five hours later, although most of the strong winds occurred away from those islands to the north of the center. Increasing northerly wind shear caused Harvey to gradually weaken back to a depression early on 19 August and to degenerate into a tropical wave by 1800 UTC that day over the central Caribbean Sea.

The remnants of Harvey moved rapidly to the west and west-northwest for the next couple of days, staying convectively active while they moved over the Yucatan Peninsula on 22 August. A low pressure area formed late that day in association with a short-lived burst of deep convection. The low moved west-northwestward into the Bay of Campeche early on 23 August and, shortly after 0600 UTC, more persistent deep convection increased near the low. By 1200 UTC, an Air Force Reserve reconnaissance aircraft found that the circulation of the low had become better-defined, indicating that Harvey had regenerated into a tropical depression when its center was located about 150 n mi west of Progreso, Mexico.

Initially, the depression was poorly organized with a large radius-of-maximum winds (RMW). This structure did not last for long as a smaller RMW formed, possibly due to concentrated deep convection near the center. Harvey began to rapidly intensify late on 23 August in an environment of light shear, very warm water and high mid-level moisture. The storm turned northward, steered around the western edge of the distant subtropical ridge, and the track gradually bent toward the northwest during the next day or two. The cyclone's rate of intensification increased early on 24 August as a large mass of deep convection formed over the center, and an eye was noted on reconnaissance observations by 1200 UTC that day. Harvey

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[1] A digital record of the complete best track, including wind radii, can be found on line at ftp://ftp.nhc.noaa.gov/atcf. Data for the current year's storms are located in the *btk* directory, while previous years' data are located in the *archive* directory.

became a hurricane later on 24 August, and by that night a well-defined eye appeared in infrared satellite pictures. The hurricane reached category 3 status by midday on 25 August while it approached the middle Texas coast and intensified into a category 4 hurricane by 0000 UTC 26 August. Harvey's center made landfall on the northern end of San Jose Island about 5 n mi east of Rockport, Texas at 0300 UTC that day. Sustained winds of 115 kt and a minimum central pressure of 937 mb are estimated for that landfall. The hurricane then made a second landfall on the Texas mainland 3 h later, slightly weaker due to land interaction, with 105 kt winds and an estimated central pressure of 948 mb southeast of Refugio on the northeast coast of Copano Bay west of Holiday Beach. Harvey rapidly weakened over land to a tropical storm within 12 h after landfall and maintained a 35-kt intensity for the next day or so, aided by the sustaining effects of the southeastern portion of its circulation remaining over water.

The steady northwestward motion of the cyclone stopped as Harvey became embedded in light steering currents between one mid-tropospheric high over the Four Corners region and another high over the northern Gulf of Mexico. The storm made a slow loop late on 26 August into 27 August, and drifted eastward or southeastward for the next few days. Although the center passed well south of the Houston Metro and Golden Triangle (southeastern Texas between Beaumont, Port Arthur and Orange) areas, torrential rains fell in these locations near a stationary front on the north and east side of Harvey (see Figs. 12-15).

The storm center moved back offshore around 0300 UTC 28 August over Matagorda Bay, its winds slightly re-strengthening with deep convection reforming near and north of the center. However, the vertical wind shear was too strong for much intensification, and Harvey reached a final peak intensity of 45 kt late on 29 August. By that time, the storm turned to the north-northeast due to a strengthening ridge over the western Atlantic, its center never having moved more than 60 n mi offshore of the Texas Coast. Extremely heavy rains, however, continued on the north and northwest side of the tropical cyclone, most concentrated then near the Beaumont-Port Arthur area. Harvey made its final landfall in southwestern Louisiana at 0800 UTC 30 August near Cameron with 40-kt sustained winds. Thereafter, the cyclone slowly weakened over land, becoming a tropical depression late on 30 August. Harvey then moved northeastward over the southern United States while producing heavy rainfall, and it transformed into an extratropical cyclone by 0600 UTC 1 September over the Tennessee Valley. The cyclone dissipated over northern Kentucky late the next day.

# METEOROLOGICAL STATISTICS

Observations in Harvey (Figs. 3 and 4) include subjective satellite-based Dvorak technique intensity estimates from the Tropical Analysis and Forecast Branch (TAFB) and the Satellite Analysis Branch (SAB), and objective Advanced Dvorak Technique (ADT) estimates from the Cooperative Institute for Meteorological Satellite Studies/University of Wisconsin-Madison. Observations also include flight-level, stepped frequency microwave radiometer (SFMR), and dropwindsonde observations from 21 flights of the 53rd Weather Reconnaissance Squadron of the U. S. Air Force Reserve Command and the NOAA Hurricane Hunters. Data and imagery from NOAA polar-orbiting satellites including the Advanced Microwave Sounding Unit (AMSU), the

NASA Global Precipitation Mission (GPM), the European Space Agency's Advanced Scatterometer (ASCAT), and Defense Meteorological Satellite Program (DMSP) satellites, among others, were also useful in constructing the best track of Harvey.

Ship reports of winds of tropical storm force associated with Harvey are given in Table 2, and selected surface observations from land stations and data buoys are given in Table 3.

## Winds and Pressure

Harvey's maximum winds of 115 kt occurred during a several hour period concluding with its first Texas landfall. That intensity was based on a blend of peak SFMR measurements of 113 kt near 2122 UTC 25 August and maximum observed 700-mb flight-level winds of 129 kt at 2037 UTC and 2330 UTC 25 August. Both of those 700-mb winds support a surface wind of about 115 kt using a typical flight-level wind to surface wind reduction. Another SFMR measurement of 113 kt at 0419 UTC 26 August is thought to be unreliable due to shoaling. The highest *observed* sustained winds on land were 96 kt near Aransas Pass, with the highest *observed* gust being 126 kt near Rockport, Texas (Table 3). It should be noted, however, that the northeastern quadrant of the hurricane came ashore in an unpopulated and unmonitored area near San Jose Island and Matagorda Island, including Aransas National Wildlife Refuge, and the maximum winds were probably not sampled by any anemometer. An instrument near the entrance of Copano Bay failed before the highest winds arrived at that location.

The minimum pressure of Harvey is estimated to be 937 mb, based on a dropsonde measurement of 938 mb with 10 kt of surface wind at 0215 UTC 26 August. The lowest observed pressure on land was 940.8 mb reported by a storm chaser in Rockport at 0331 UTC 26 August. Another storm chaser reported a pressure of 932.8 mb in Rockport at about the same time, but this observation is questionable because other pressure readings in the area were several mb higher. It is also possible that this pressure was observed in an eyewall mesovortex, which would not be representative of the overall circulation.

## Storm Surge[2]

The combined effect of the surge and tide produced maximum inundation levels of 6 to 10 ft above ground level to the north and east of Harvey's center landfalls in Texas in the back bays between Port Aransas and Matagorda, including Copano Bay, Aransas Bay, San Antonio Bay, and Matagorda Bay. Fig. 5 provides an analysis of maximum coastal inundation heights along the coasts of Texas and Louisiana from Harvey. The highest inundations (8 to 10 ft above ground level) likely occurred along the western shores of San Antonio Bay and adjacent Hynes Bay. The highest measured water level by a tide gauge was 6.7 ft above Mean Higher High Water (MHHW) at a Texas Coastal Ocean Observing Network (TCOON) site at Port Lavaca. Other notable TCOON tide gauge observations include 5.5 ft MHHW at Seadrift, 5.3 ft MHHW at Port Aransas, and 4.8 ft MHHW at the Aransas National Wildlife Refuge. Fig. 6 shows water levels relative to MHHW measured at tide gauges along the coasts of Texas and Louisiana.

Data from United States Geological Survey (USGS) storm tide pressure sensors and high water mark surveys from the back bays between Port Aransas and Matagorda provide evidence of inundations higher than those suggested solely by the National Ocean Service (NOS) or TCOON tide gauges. A sensor installed in Austwell, Texas, along the shore of Hynes Bay recorded a wave-filtered water level of 9.49 ft above the North American Vertical Datum of 1988 (NAVD88), which converts to 8.7 ft MHHW. In addition, a sensor installed in Port Lavaca recorded a water level of 8.82 ft NAVD88 (8.1 ft MHHW), while a sensor located in the upper reaches of Caranchua Bay measured a water level of 9.17 ft NAVD88 (8.4 ft MHHW). Various high water mark surveys conducted by the USGS and the National Weather Service (NWS) between Austwell and the Aransas National Wildlife Refuge suggested water levels as high as 11 to 12 ft MHHW, but these estimates likely contain the effects of wave runup and thus may be too high to represent actual inundation. The USGS storm tide sensor data, with considerations of sampling gaps, suggest that the highest inundations from Harvey were 8 to 10 ft above ground level.

Copano Bay, where Harvey made its second Texas landfall, also had significant storm surge flooding of 4 to 7 ft above ground level. A TCOON gauge near the entrance to Copano Bay recorded a maximum water level of 4.0 ft MHHW while a nearby USGS storm tide sensor measured a wave-filtered water level of 5.79 ft NAVD88 (5.1 ft MHHW). A survey conducted by the Corpus Christi NWS office also measured up to 7 ft of inundation above ground level at Holiday Beach on the northeastern side of Copano Bay.

Similar coastal flooding of 4 to 7 ft above ground level occurred in locations south of Port Aransas to the north entrance of the Padre Island National Seashore. In addition to the aforementioned Port Aransas gauge, which measured 5.3 ft MHHW, the TCOON gauge at

[2] Several terms are used to describe water levels due to a storm. **Storm surge** is defined as the abnormal rise of water generated by a storm, over and above the predicted astronomical tide, and is expressed in terms of height above normal tide levels. Because storm surge represents the deviation from normal water levels, it is not referenced to a vertical datum. **Storm tide** is defined as the water level due to the combination of storm surge and the astronomical tide, and is expressed in terms of height above a vertical datum, i.e. the North American Vertical Datum of 1988 (NAVD88) or Mean Lower Low Water (MLLW). **Inundation** is the total water level that occurs on normally dry ground as a result of the storm tide, and is expressed in terms of height above ground level. At the coast, normally dry land is roughly defined as areas higher than the normal high tide line, or Mean Higher High Water (MHHW).

Packery Channel measured a water level of 4.7 ft MHHW, and the USGS surveyed a high water mark of 6.4 ft above ground level near Port Aransas. Along the Gulf of Mexico side of the barrier island, a water level of 3.5 ft MHHW was measured at the Bob Hall Pier. Due to offshore winds on the west side of Harvey, less flooding (generally 1 to 3 ft above ground level) occurred in Corpus Christi Bay. A tide gauge at the USS Lexington in Corpus Christi measured a water level of 1.0 ft above MHHW. Less than 3 ft of inundation also occurred to the south in areas adjacent to Laguna Madre, including Padre Island.

Onshore winds to the east of Harvey's Texas landfall locations likely produced storm surge inundations of 4 to 7 ft above ground level along the barrier island from Port Aransas to Matagorda, however that area is unpopulated with no tide gauge observations. To the north and east, tide gauge observations indicate that water levels of 2 to 4 ft above ground level occurred from Matagorda through the upper Texas coast eastward to the central Louisiana coast due to storm surge. For example, the TCOON tide gauge at High Island recorded a peak water level of 4.1 ft MHHW while the gauge at San Luis pass measured a water level of 3.3 ft MHHW. In Louisiana, an NOS gauge at the Freshwater Canal Locks recorded a peak water level of 3.2 ft MHHW.

It must be noted that several tide gauges, particularly those in upper Galveston Bay near Houston and in Sabine Lake near Beaumont and Port Arthur, recorded peak water levels that were significantly affected by excessive rainfall runoff from Harvey's historic heavy rains. The most extreme cases were from two TCOON gauges on the east side of Houston: a station in Manchester measured a peak water level of 10.5 ft MHHW and a gauge at Lynchburg Landing recorded a peak water level of 7.3 ft MHHW. While these water levels are representative of the type of inundation that occurred in parts of the Houston area, the high values reported by these gauges were largely caused by excessive rainfall runoff and not storm surge.

## *Rainfall and Flooding*

Harvey was the most significant tropical cyclone rainfall event in United States history, both in scope and peak rainfall amounts, since reliable rainfall records began around the 1880s. The highest storm total rainfall report from Harvey was 60.58 inches near Nederland, Texas, with another report of 60.54 inches from near Groves, Texas. Both of these values (and from five other stations) exceed the previously accepted United States tropical cyclone storm total rainfall record of 52.00 inches at Kanalohuluhulu Ranger Station, Hawaii, in August of 1950 from Hurricane Hiki. A map of the storm-total rainfall associated with Harvey (or its post-tropical phase over the Ohio Valley) is given in Fig. 7.

For the continental United States, the previous tropical cyclone rainfall record was 48.00 inches in Medina, Texas from Tropical Storm Amelia in 1978. It is remarkable that during Harvey, eighteen values over 48 inches were recorded (Fig. 8) across southeastern Texas, with 36 to 48 inches recorded in the Houston metro area. These rains caused catastrophic flooding in Harris and Galveston counties, with 9 out of the 19 official river gauges in Harris County (which includes the city of Houston) recording all-time high flood stages. Table 3 shows selected heavy rain totals,

and a full listing of rainfall reports can be found in a supplementary data file at: https://www.nhc.noaa.gov/data/tcr/supplemental/harvey_rain.xlsx.

Due to the severe limitations of measuring rainfall of this magnitude (e.g. many standard rain gauges filled up to a ~12 inch maximum and were unable to be emptied due the extreme rain rates), it is useful to look at the peak rain totals in other ways The multi-radar, multi-sensor quantitative precipitation estimation radar estimates (Fig. 9, for more details see: https://www.nssl.noaa.gov/about/events/review2015/science/files/Zhang_NSSLReview2015_MRMS-Hydro.pdf) were as high as 65-70 inches in southeastern Texas. Interestingly, there were few rainfall reports near the center of the radar-estimated maximum during Harvey in the vicinity of Port Arthur and the Lower Neches Wildlife Management Area (Fig. 9), and these radar estimates represent the highest rainfall that could have occurred (outside of the actual measurements).

While the peak rainfall amounts were exceptional over Texas, the areal extent of heavy rainfall is truly overwhelming, literally and figuratively. A comparison of historic United States tropical cyclone rainfall events is shown in Figs. 10a and b, with Harvey being compared to Allison (2001) and Beulah (1967). Large sections of southeastern Texas received 3 ft or more of rainfall in Harvey, whereas only very small portions of the Houston metro area had those totals in Allison. Beulah had one of the largest 10 inch or greater rain shields on record, similar to Harvey's. For any total above 15 inches, however, Harvey's area(s) are considerably larger. In fact, NOAA recently completed an analysis of annual exceedance probabilities for southeastern Texas (Fig. 11) after Harvey, with a large portion of that area experiencing a flood with less than a 1-in-1000 (0.1%) chance of occurring in any given year (e.g., a 1000-year or greater flood). While established records of this nature are not kept, given the exceptional exceedance probabilities, it is unlikely the United States has ever seen such a sizable area of excessive tropical cyclone rainfall totals as it did from Harvey.

The meteorological situation that caused Harvey to produce these extreme rains deserves additional explanation. While Harvey was very slow moving over Texas, not all drifting cyclones produce such torrential rain totals, and it is notable that the heaviest rainfall fell outside of the core of the cyclone. Harvey moved into a somewhat baroclinic environment over Texas, with slightly cooler and drier air over the southern United States behind a weak stationary front (Fig. 12). The weak front was situated across the Houston metro area from 26-27 August, enhancing surface convergence and lift within the very warm and humid air on the eastern side of Harvey, leading to several episodes of heavy rain. Upper-level divergence was also occurring near the front, further contributing to large and intense rain bands. The rain rates observed in these bands were exceptional, with 6.8 inches of rain in just one hour documented in southeastern Houston from extremely heavy rain bands training over the same location. The front hardly moved from 27-28 August (Figs. 13, 14), leading to the extreme rainfall totals in the Houston metro area since the main inflow band originated over the very warm waters of the northwestern Gulf of Mexico, which provided multiple influxes of warm and humid air. It should be noted that while the magnitude of this event was unprecedented, the synoptic situation was not, and previously has been associated with other tropical cyclone flood events near the coast.

By late on 28 August, the front was in the vicinity of the Beaumont/Port Arthur area, and Harvey's center had moved offshore. The cyclone had begun to lose some tropical characteristics with drier air wrapping around the core, but it still was advecting warm and moist air over the frontal boundary along the Texas/Louisiana coasts, producing abundant isentropic lift. The

heaviest rainfall was occurring in a deformation zone on the north or northwest side of the cyclone, near the stationary front. While the rainfall was not as heavy as the 26 August event, 2-3 inches of rain per hour were still occurring in areas of Houston. The heaviest rain shifted eastward into Jefferson County on 28-30 August, which was located in the deformation zone and near the stationary front (Fig. 15), leading to the absolute rainfall maxima in that area.

Harvey also produced heavy rain over Louisiana, with a peak amount of 23.71 inches recorded west of Vinton. Radar data, however, suggests an estimate of about 40 inches for a maximum value, which is considered more representative of peak rainfall in that state since there were few observations over extreme southwestern Louisiana (e.g. Fig. 9). Lesser totals were measured as Harvey moved farther into the southern United States and Tennessee Valley on 31 August - 1 September, although there was a local maximum of about a foot of rain reported in Tennessee. These rains caused some significant flooding in Tennessee, especially in Robertson County.

### *Tornadoes*

Harvey was a prolific tornado producer. There were 57 tornadoes preliminarily reported during Harvey (Fig. 16), about half of which occurred near and south of the Houston metro area. Over 150 tornado warnings were issued during the event. Tornadoes were also noted in Louisiana, Mississippi, Alabama and Tennessee as the cyclone moved near or over those states. Fortunately, almost all of the tornadoes were relatively weak, of EF-0 and EF-1 intensity, with generally minor damage, few injuries and no deaths attributed to them.

## CASUALTY AND DAMAGE STATISTICS

Harvey is responsible for at least 68 direct deaths[3] in the United States, all in Texas. Over half of the deaths (36) were in Harris County in the Houston metro area. A county-by-county listing of the direct deaths is available in Table 4. All but three of the deaths were from freshwater flooding, and none of the deaths can be linked to the storm surge, which is quite remarkable for a category 4 hurricane landfall. Still, Harvey is the deadliest U.S. hurricane in terms of direct deaths since Sandy (2012) and is the deadliest hurricane to hit Texas since 1919. About 35 additional deaths are ascribed to indirect causes, such as electrocution, motor-vehicle crashes and isolation from necessary medical services. Four people were reported injured by a tornado north of Reform, Alabama.

[3] Deaths occurring as a direct result of the forces of the tropical cyclone are referred to as “direct” deaths. These would include those persons who drowned in storm surge, rough seas, rip currents, and freshwater floods. Direct deaths also include casualties resulting from lightning and wind-related events (e.g., collapsing structures). Deaths occurring from such factors as heart attacks, house fires, electrocutions from downed power lines, vehicle accidents on wet roads, etc., are considered indirect” deaths.

The latest NOAA damage estimate from Harvey is $125 billion, with the 90% confidence interval ranging from $90 to $160 billion. The mid-point of the estimate would tie Katrina (2005) as the costliest United States tropical cyclone, which was also $125 billion (see https://www.ncdc.noaa.gov/billions/). However, the unadjusted costliest tropical cyclone list is not the most relevant record to examine because of inflation and other cost increases since 2005. A more reasonable comparison uses the Consumer Price Index (CPI)-adjusted technique, which modifies 2005 dollars to 2017. The adjustments make Katrina's total $161.3 billion in 2017 dollars, leading to Harvey being the 2nd costliest U.S. tropical cyclone. There is, however, still a large uncertainty in the total damage estimate (hence the large confidence interval). This is due to many factors, including that a majority of the residential flood loss claims are from outside the 500-year flood plain, where there is low National Flood Insurance Program (NFIP) participation, with tens of thousands of claims still outstanding.

The damage caused by Harvey's flooding was catastrophic over a large area of southeastern Texas. Over 300,000 structures in that region were flooded, with up to 500,000 cars reported flooded as well (e.g., Fig. 17). About 336,000 customers lost power during the hurricane. An estimated 40,000 flood victims were evacuated to or took refuge in shelters across Texas or Louisiana. FEMA reported that about 30,000 water rescues were conducted during Harvey.

The exceptional rainfall fell over some of the most densely populated areas of the U.S. Gulf Coast. Widespread flooding of homes and businesses occurred from the Houston metro area southward, and the floodwaters inundated major roads such as I-10, I-45, and US-59. Record water levels were observed on Buffalo Bayou, Clear Creek, Dickinson Bayou and Cypress Creek. Some of the hardest hit areas from flooding in the Houston metro area extended from Humble to Lake Houston, including the neighborhoods of Northshore, Bellaeu Woods, Riviera, Treasure Cove, Kings Lake Estates, Kings River, Kings Crown Estates, Kings River Estates, Atascocita Shores, Atascocita West, Ramblewood, Walden Subdivisions, and along the West Lake Houston Parkway, North Houston Ave., Thelma Road, Hamblen Road and Aqua Vista Drive. These were just some of the hundreds of subdivisions that suffered catastrophic flooding. During the height of the storm, controlled releases from Addicks and Barker Reservoirs were performed to prevent catastrophic dam failures, which further flooded some of the areas above. Record flooding along the east fork of the San Jacinto River led to flooded homes in Northwood Country Estates and River Terrace.

Farther south, catastrophic flooding was reported in League City, Friendswood and Dickinson in Galveston County, with extreme water levels leading to numerous water rescues across these areas and downtown Houston (Fig. 18). Primary and secondary roads in the area were inundated, including Bay Area Blvd., FM 528 and FM 518. At least 160,000 structures were flooded in Harris and Galveston counties.

Beyond the Houston metro area, the most serious flood damage was noted farther east in Texas over Jefferson, Orange, Hardin and Tyler counties, with about 110,000 structures (about one-third of the total structures damaged by Harvey) in those counties flooded. Flooding induced by widespread rainfall amounts of 40 inches resulted in several oil and gas refineries in the Golden Triangle area (southeastern Texas between Beaumont, Port Arthur and Orange) going offline for days, and consequently gas prices in the United States spiked to their highest levels in two years. Record water levels were seen on Pine Island Bayou, the Lower Neches River and Cow Bayou.

A bridge collapse occurred at the Highway 96 Bridge over Village Creek near Silsbee, and flood waters inundated parts of I-10 in Rose City, Vidor and near the city of Orange. Historic flooding was also reported in many cities across these counties, including Port Arthur, Lumberton, Warren, Groves, Bevil Oaks, Sour Lake, Hamshire, Fannett, China, Silsbee, Lakeview, Mauriceville and northeastern Beaumont.

Near the initial landfall location in Texas, wind damage was extreme in Aransas County, Nueces County, Refugio County and the eastern part of San Patricio County. Approximately 15,000 homes were destroyed in these areas, with another 25,000 damaged, and extensive tree damage was noted. Generally, the damage was most severe in the areas adjacent to Aransas Bay and Copano Bay, with the city of Rockport hit particularly hard. Coastal areas of the counties above and Calhoun County were inundated with storm surge, and many marinas reported serious damage or destruction of boats, docks and piers. This includes State Highway 361 which was inundated along the entire stretch of Mustang Island. The surge also damaged or destroyed many coastal structures in Port Aransas, Holiday Beach, Copano Village, Lamar, Seadrift, North Padre Island and Mustang Island. Erosion from surge near the Packery Channel caused an interruption to the primary water supply to Port Aransas for six days. Corpus Christi was spared the worst of the hurricane's effects, with widespread but mostly minor damage reported. At the peak, roughly 220,000 customers lost power.

In Fort Bend County, major flooding occurred with both the Brazos and San Bernard Rivers experiencing record floods. Major-to-record flooding occurred along the Brazos River from Richmond to Rosharon. Significant home flooding occurred in areas of Simonton, Richmond, Rosenburg, and Thompsons. Nearly 200,000 people were evacuated due to levee concerns and restrictions. Major-to-record flooding also occurred on the San Bernard River at both East Bernard and Boling, with the hardest hit area being Tierra Grande. At least 8,500 homes in this county were damaged by Harvey.

In Brazoria County, the Brazos and San Bernard Rivers experienced record water levels, which caused widespread floods across the county. The hardest hit communities were in Baileys Prairie, Richard and West Columbia. Widespread major flooding on the Brazos River and Oyster Creek led to numerous roads and homes flooding in Columbia Lakes, Mallard Lakes, Great Lakes, Riverside Estates and the Bar X Ranch subdivisions, as well as homes on CR 39. Flooding damaged the bridge over Cow Creek at CR 25, making it impassable. Major flooding also occurred along the San Bernard River at Sweeny with widespread inundation of the west floodplain. The Phillips 66 refinery took on water near Little Linville Bayou. Hanson Riverside Park was inundated, and water overtopped the Phillips Terminal, halting all vessel traffic. High flows from the Brazos and San Bernard Rivers caused navigation problems for several weeks. Over 9,000 homes experienced flood damage from the storm.

In Wharton County, widespread catastrophic flooding occurred from both the Colorado and San Bernard Rivers, causing Highway 59 to close between Hungerford and El Campo. The flooding inundated areas of Wharton, with hundreds of homes and businesses under water in many communities including Hobben Oaks, Bear Bottom, Elm Grove, River Valley and Pecan Valley. Other areas such as Glenflora, Peach Acres and the Orchard were hard hit. Major-to-record flooding also occurred on the San Bernard River at both East Bernard and Boling, with the hardest hits areas being El Lobo and New Gulf. Major lowland flooding occurred with many

homes (including some on the second-story) and businesses being inundated, and the cotton crop was decimated. An estimated 2,000 homes were damaged or destroyed in the county.

Major lowland flooding occurred in Matagorda County along the Tres Palacios River. Many roadways were under water, and homes in the El Dorado Country, Oak Grove, and Tres Palacios Oaks subdivisions flooded. Major flooding also occurred on the Colorado River at Bay City as levees were overtopped by 2 ft of water. High flows from the Colorado and Tres Palacios Rivers impacted river navigation for several weeks. Roughly 2,900 homes were damaged in the county.

In San Jacinto County, major lowland flooding occurred on the Trinity River near Goodrich with damage and debris noted near the boat ramp and channel in proximity to the river gauge. Major flooding occurred upstream near Lake Livingston, with roads and many homes south of the lake being inundated. About 3,300 homes were damaged in the county.

Major-to-record flooding occurred in Liberty County along the Trinity River with numerous roads inundated including FM 787. Many homes and subdivisions were either cut off or inundated, specifically north of the city of Liberty and in the Grenada Lakes Estates subdivision. Significant damage occurred along the banks of the river due to high flows and several utility lines were severed due to the loss of poles in the vicinity of the Romayor gauge. Record river levels were also observed on the east fork of the San Jacinto River causing significant flooding in Cleveland, Williams and Plum Grove. High flows caused significant scouring of the state 105 (business) road; other roads were washed out as well, with bridge washouts or closures observed in many parts of the county. At least 1,000 homes were damaged in the county.

In Chambers County, record floods over the lowlands occurred along the Trinity River. Cedar Bayou was out of its banks in many locations, with significant flooding observed in Baytown. Numerous roads and homes were inundated across the county, including extensive flooding in the Milam Bend subdivision. High flows from the Trinity River impacted the navigation community for several weeks. An estimated 3,000 homes were damaged, and numerous businesses had significant damage.

In Jasper and Newton counties, an estimated 20 to 40 inches of rain fell across the area. This rainfall lead to major flooding, with over 4,000 homes flooded in Jasper County and about 2,000 in Newton County. The hardest hit areas were Kirbyville, Buna, Weiss Bluff, Trout Creek, Call and along the Sabine River. River gauges on the Neches and Sabine rivers had levels up to their second highest crests on record, and Big Cow Creek at Newton recorded its highest on record.

In Fayette County, a widespread area of 25 to 30 inches of rain produced major flooding along the Colorado River and produced the third highest crest ever at La Grange. Much of the city of La Grange below Waters Street was flooded. There were over 400 flooded homes and businesses flooded in La Grange and across the county. Two hundred of the homes sustained major flood damage including dozens of businesses that were flooded in downtown La Grange. Less severe flooding occurred in DeWitt County near Cuero from the Guadalupe River.

Louisiana received relatively minor damage compared to Texas. Still, roughly 2,000 homes flooded in Calcasieu, Beauregard, and Cameron Parishes, with many flooded roads and rivers noted. Many of these homes were located along the Sabine River, which recorded its

second highest crest on record at Orange. Eastern sections of Lake Charles, Chennault eastward to Iowa and northward to Moss Bluff were hit with flooding late on 27 August.

Very heavy rain in Tennessee caused minor damage. The Memphis area had flooding and over 19,000 customers lost power, with winds gusting to 52 kt at the airport. More significant flooding was reported in Robertson County (Nashville area), with 13 residents in the Chestnut Flats Apartment near the Nashville Fairgrounds evacuated due to the high water. In addition, the downtown Nashville Goodwill Industries reported major flooding, and about 10,000 customers were out of power at one time in that city.

Much of the damage summaries in this section came from the Post Tropical Cyclone Reports from the Corpus Christi, San Antonio, Houston and Lake Charles NWS offices. Further local details are available in their summaries at: http://www.weather.gov/crp/hurricane_harvey, https://www.weather.gov/ewx/wxevent-2017harvey, http://www.weather.gov/hgx/hurricaneharvey and https://www.weather.gov/lch/2017harvey.

# FORECAST AND WARNING CRITIQUE

NHC anticipated with limited lead time Harvey's formation to the east of the Caribbean Islands (Table 5a). NHC introduced the 5-day potential for tropical cyclone development into the Tropical Weather Outlook (TWO) in the low category (<40%) about 4 days before genesis occurred. It raised the probability to the medium (40-60%) category 3 days before formation, and the 2-day probability only reached the medium category 12 h before genesis occurred. In neither forecast time period did the probability reach the high category (>60%). The re-formation of Harvey was well-forecast by NHC (Table 5b), with the system re-entering the outlook 78 h before genesis occurred again with a medium chance of formation during the next 5 days. The remnants of Harvey in the Caribbean were given a high (>60%) chance of genesis in the 2-day outlook 42 h before reformation occurred — an excellent forecast by current standards.

A verification of NHC official track forecasts for Harvey is given in Table 6a. Official forecast track errors were much lower than the mean official errors for the previous 5-yr period, although the OCD5 (climatology) errors were also quite low, indicating that these forecasts were "easier" than average. A homogeneous comparison of the official track errors with selected guidance models is given in Table 6b. Generally the NHC official forecast (OFCL) beat much of the guidance except for the consensus aids (TVCN, TVCX). Among the individual deterministic models, the ECMWF (EMXI), UKMET (EGRI) and COAMPS (CTCI) models all did well at some of the forecast times, mostly centered in the middle range of the forecast period. Much of the GFS-based guidance (GFSI, AEMI and HWFI) did not have a particularly good performance for Harvey.

A verification of NHC official intensity forecasts for Harvey is given in Table 7a. Official forecast intensity errors were above the mean official errors for the previous 5-yr period through 48 hours, then considerably lower than average after that through 5 days. A homogeneous comparison of the official intensity errors with selected guidance models is given in Table 7b. The NHC intensity forecast performed better than all of the intensity model guidance at 12, 96 and

120 h but was worse than all of guidance at 36 and 48 h. This unusual dichotomy appears to be due to the cyclone weakening faster than expected over land at 36 and 48 h, but NHC correctly forecasting Harvey to stay a weak cyclone at long range, with almost every forecast point verifying over land. In general, the intensity model consensus (IVCN) was the best model aid, and was superior to any other forecast (including OFCL) from 24-48 h. The Decay-SHIPS (DSHP) and Florida State Superensemble (FSSE) models had relatively poor performances compared to the other guidance.

Initially, the rapid intensification (RI) of Harvey after its re-formation was not well-anticipated, but most of the guidance had Harvey near hurricane intensity before landfall in Texas (Fig. 19). The next day, however, most of the historically reliable guidance aids showed Harvey rapidly intensifying, although the guidance was still too low (Fig. 20). A NHC Special Advisory issued at 1800 UTC 24 August, 33 h before landfall (not shown), forecast RI and verified within 5 kt of the intensity near landfall, which was an outstanding forecast.

Watches and warnings for winds associated with Harvey are given in Table 8. A Hurricane Watch was first issued at 1500 UTC 23 August and a Hurricane Warning was first issued at 0900 UTC 24 August. These watches and warnings were issued about 48 and 36 hours, respectively, before tropical-storm-force winds affected the Texas coast, close to the desired lead times. The possibility of hurricane-force winds to affect the Texas coast was first mentioned in the Tropical Weather Outlook, over 72 hours before they occurred, which is believed to be a first for a system that had not yet (re)formed.

The NHC began providing direct support to emergency managers on 22 August, as Harvey was re-forming over the Yucatan Peninsula and continued through 30 August, when Harvey made its final landfall in SW Louisiana. This decision support included calls and briefings coordinated through the FEMA Hurricane Liaison Team, embedded at the NHC. The briefings included the states of Texas and Louisiana, FEMA Region 6 as well as Federal/State video-teleconferences. The NHC also collaborated with the affected NWS offices to ensure a consistent message, and NWS meteorologists provided Impact-based Decision Support Services (IDSS), for local and state emergency management offices during this event. In addition, the NHC director maintained direct communications with senior state emergency management officials to discuss the evolving threat to Texas. For the first part of Harvey's track, the NHC provided support to many government meteorological services for areas around the Caribbean Sea, including Barbados (which has responsibility for Dominica, St. Vincent and the Grenadines), France (for Martinque and Guadeloupe), St. Lucia, Aruba, Belize and Mexico.

At various points in time, the NWS issued storm surge warnings for portions of the Texas coast from Port Mansfield to High Island and for portions of the Louisiana coast from Holly Beach to Morgan City. The NWS issued storm surge watches for other portions of the Texas coast south of Port Mansfield to the mouth of the Rio Grande, east of High Island to Holly Beach, and for the coasts of Galveston Bay and Sabine Lake. The NWS issued the initial Storm Surge Watch for Harvey along the Texas coast from Port Mansfield to High Island at 1500 UTC 23 August (Table 9). The initial Storm Surge Warning was issued from Port Mansfield to San Luis Pass, Texas, at 0900 UTC 24 August. Water level observations indicate that at least 3 ft of inundation (which NHC uses as an initial threshold for the storm surge watch/warning) occurred in areas within the bounds of the storm surge warning area in Texas (see Fig. 6).

The NHC's first forecast for maximum storm surge heights (at 1500 UTC 23 August) was 4 to 6 ft above ground level within the storm surge watch area, and that forecast was gradually raised to 6 to 12 ft above ground level within the area between the north entrance of the Padre Island National Seashore to Sargent at 1800 UTC 24 August. Later that evening, maximum storm surge heights were increased to 9 to 13 ft above ground level in the area from Port Aransas to Port O'Connor. The maximum observed storm surge heights of 8 to 10 ft above ground level occurred within that outlined region in the back bays between Port Aransas and Port O'Connor.

Before the Louisiana landfall of Harvey, the NWS issued a Storm Surge Watch from Port Bolivar, Texas, to Morgan City, Louisiana, at 2100 UTC 28 August, and a portion of that area from Holly Beach to Morgan City was upgraded to a Storm Surge Warning at 2100 UTC 29 August for expected inundations of 2 to 4 ft above ground level, especially in Vermilion Bay. Although there were no tide gauges where the highest inundation occurred, storm surge simulation hindcasts indicate that 2 to 4 ft of inundation above ground level occurred in portions of Vermilion Bay.

The storm surge watches and warnings for Harvey were the first operational issuance of these products for the NWS, which have been in development for the past several years. It is hoped that this new capability, along with the storm surge inundation graphic and major outreach efforts during that time, were factors in there being no surge-related deaths from this category 4 hurricane. In addition, an NHC media pool was in full operation from 24-26 August to provide live briefings to national and local television outlets in both English and Spanish, and an additional 200 media phone interviews were conducted. NHC was also active on social media to keep the public informed in real-time on the latest NHC/NWS forecasts and warnings, with posts on Twitter generating 35 million impressions and Facebook posts reaching more than 5.5 million users and causing 2.9 million post engagements.

The rainfall forecasts for Harvey, issued by the Weather Prediction Center (WPC), were the highest on record for any U.S. tropical cyclone event and deserve some comment. When Harvey re-formed in the Gulf of Mexico, the initial maximum rainfall forecast was for 20" in southeastern Texas (Fig. 21). These rainfall forecasts were gradually increased to a peak of 40" several hours before Harvey made landfall in Texas, roughly 24-36 hours before the extreme rains began in the Houston metro area. These totals were further raised to 50" about a day before the center of Harvey left Texas.

Table 1. Best track for Hurricane Harvey, 17 August – 1 September 2017.

| Date/Time (UTC) | Latitude (°N) | Longitude (°W) | Pressure (mb) | Wind Speed (kt) | Stage |
|---|---|---|---|---|---|
| 16 / 0600 | 13.7 | 45.8 | 1013 | 25 | low |
| 16 / 1200 | 13.7 | 47.4 | 1010 | 25 | " |
| 16 / 1800 | 13.6 | 49.0 | 1009 | 25 | " |
| 17 / 0000 | 13.6 | 50.6 | 1010 | 25 | " |
| 17 / 0600 | 13.4 | 52.0 | 1008 | 25 | tropical depression |
| 17 / 1200 | 13.1 | 53.4 | 1008 | 30 | " |
| 17 / 1800 | 13.0 | 55.0 | 1004 | 35 | tropical storm |
| 18 / 0000 | 13.0 | 56.6 | 1003 | 40 | " |
| 18 / 0600 | 13.0 | 58.4 | 1004 | 40 | " |
| 18 / 1000 | 13.1 | 59.6 | 1004 | 40 | " |
| 18 / 1200 | 13.1 | 60.3 | 1004 | 40 | " |
| 18 / 1500 | 13.2 | 61.2 | 1004 | 40 | " |
| 18 / 1800 | 13.2 | 62.2 | 1005 | 35 | " |
| 19 / 0000 | 13.4 | 64.0 | 1005 | 35 | " |
| 19 / 0600 | 13.5 | 65.7 | 1005 | 35 | " |
| 19 / 1200 | 13.7 | 67.5 | 1006 | 30 | tropical depression |
| 19 / 1800 | 13.8 | 69.2 | 1007 | 30 | tropical wave |
| 20 / 0000 | 14.0 | 71.0 | 1007 | 30 | " |
| 20 / 0600 | 14.2 | 72.9 | 1007 | 30 | " |
| 20 / 1200 | 14.4 | 75.0 | 1006 | 30 | " |
| 20 / 1800 | 14.7 | 76.8 | 1007 | 30 | " |
| 21 / 0000 | 15.1 | 78.6 | 1007 | 25 | " |
| 21 / 0600 | 15.7 | 80.5 | 1008 | 25 | " |
| 21 / 1200 | 16.4 | 82.5 | 1008 | 25 | " |
| 21 / 1800 | 17.3 | 84.6 | 1008 | 25 | " |
| 22 / 0000 | 18.0 | 86.4 | 1008 | 25 | " |

| | | | | | |
|---|---|---|---|---|---|
| 22 / 0600 | 18.6 | 87.8 | 1009 | 25 | " |
| 22 / 1200 | 19.4 | 88.8 | 1010 | 25 | " |
| 22 / 1800 | 20.0 | 89.7 | 1010 | 25 | low |
| 23 / 0000 | 20.5 | 90.7 | 1009 | 25 | " |
| 23 / 0600 | 20.9 | 91.6 | 1008 | 25 | " |
| 23 / 1200 | 21.4 | 92.3 | 1006 | 30 | tropical depression |
| 23 / 1800 | 21.6 | 92.4 | 1005 | 35 | tropical storm |
| 24 / 0000 | 22.0 | 92.5 | 1003 | 40 | " |
| 24 / 0600 | 22.8 | 92.6 | 997 | 50 | " |
| 24 / 1200 | 23.7 | 93.1 | 986 | 60 | " |
| 24 / 1800 | 24.4 | 93.6 | 978 | 70 | hurricane |
| 25 / 0000 | 25.0 | 94.4 | 973 | 80 | " |
| 25 / 0600 | 25.6 | 95.1 | 966 | 90 | " |
| 25 / 1200 | 26.3 | 95.8 | 949 | 95 | " |
| 25 / 1800 | 27.1 | 96.3 | 943 | 105 | " |
| 26 / 0000 | 27.8 | 96.8 | 941 | 115 | " |
| 26 / 0300 | 28.0 | 96.9 | 937 | 115 | " |
| 26 / 0600 | 28.2 | 97.1 | 948 | 105 | " |
| 26 / 1200 | 28.7 | 97.3 | 978 | 65 | " |
| 26 / 1800 | 29.0 | 97.5 | 991 | 50 | tropical storm |
| 27 / 0000 | 29.2 | 97.4 | 995 | 45 | " |
| 27 / 0600 | 29.3 | 97.6 | 998 | 40 | " |
| 27 / 1200 | 29.1 | 97.5 | 998 | 35 | " |
| 27 / 1800 | 29.0 | 97.2 | 998 | 35 | " |
| 28 / 0000 | 28.8 | 96.8 | 997 | 35 | " |
| 28 / 0600 | 28.6 | 96.5 | 997 | 40 | " |
| 28 / 1200 | 28.5 | 96.2 | 997 | 40 | " |
| 28 / 1800 | 28.4 | 95.9 | 997 | 40 | " |
| 29 / 0000 | 28.2 | 95.4 | 996 | 40 | " |
| 29 / 0600 | 28.1 | 95.0 | 996 | 40 | " |

| | | | | | |
|---|---|---|---|---|---|
| 29 / 1200 | 28.2 | 94.6 | 995 | 40 | " |
| 29 / 1800 | 28.5 | 94.2 | 993 | 45 | " |
| 30 / 0000 | 28.9 | 93.8 | 994 | 45 | " |
| 30 / 0600 | 29.4 | 93.6 | 990 | 40 | " |
| 30 / 0800 | 29.8 | 93.5 | 991 | 40 | " |
| 30 / 1200 | 30.1 | 93.4 | 992 | 40 | " |
| 30 / 1800 | 30.6 | 93.1 | 996 | 35 | " |
| 31 / 0000 | 31.3 | 92.6 | 998 | 30 | tropical depression |
| 31 / 0600 | 31.9 | 92.2 | 999 | 25 | " |
| 31 / 1200 | 32.5 | 91.7 | 1001 | 20 | " |
| 31 / 1800 | 33.4 | 90.9 | 1001 | 25 | " |
| 01 / 0000 | 34.1 | 89.6 | 1000 | 30 | " |
| 01 / 0600 | 34.9 | 88.2 | 1002 | 30 | extratropical |
| 01 / 1200 | 36.0 | 87.1 | 1002 | 25 | " |
| 01 / 1800 | 36.5 | 86.4 | 1004 | 20 | " |
| 02 / 0000 | 37.2 | 85.6 | 1007 | 20 | " |
| 02 / 0600 | 37.9 | 84.9 | 1009 | 20 | " |
| 02 / 1200 | 38.2 | 84.7 | 1013 | 15 | " |
| 02 / 1800 | | | | | dissipated |
| 18 / 1000 | 13.1 | 59.6 | 1004 | 40 | landfall on the southern end of Barbados |
| 18 / 1500 | 13.2 | 61.2 | 1004 | 40 | landfall on St. Vincent |
| 26 / 0300 | 28.0 | 96.9 | 937 | 115 | minimum pressure, maximum winds and landfall on San Jose Island, TX |
| 26 / 0600 | 28.2 | 97.1 | 948 | 105 | landfall on the northeast end of Copano Bay, west of Holiday Beach, TX |
| 30 / 0800 | 29.8 | 93.5 | 991 | 40 | landfall near Cameron, LA |

Table 2. Selected ship reports with winds of at least 34 kt for Harvey.

| Date/Time (UTC) | Ship call sign | Latitude (°N) | Longitude (°W) | Wind dir/speed (kt) | Pressure (mb) |
|---|---|---|---|---|---|
| 25 / 0600 | WDE958 | 27.0 | 91.7 | 080 / 40 | 1006.7 |
| 25 / 0600 | A8PQ7 | 27.4 | 91.9 | 130 / 35 | 1008.0 |
| 25 / 0600 | WBYQ | 27.6 | 91.8 | 090 / 37 | 1010.1 |
| 25 / 0600 | WDF476 | 28.0 | 92.7 | 140 / 55 | 1009.4 |
| 25 / 0700 | A8PQ7 | 27.3 | 91.8 | 130 / 35 | 1008.0 |
| 25 / 0900 | WLMQ | 22.1 | 92.0 | 230 / 45 | 1007.2 |
| 25 / 1100 | C6FN5 | 25.9 | 88.6 | 020 / 35 | 1008.1 |
| 25 / 1200 | WNFQ | 28.0 | 92.7 | 120 / 35 | 1008.3 |
| 25 / 1500 | LAIG7 | 28.5 | 93.3 | 140 / 42 | 1012.0 |
| 26 / 0500 | 3FMK7 | 28.9 | 93.2 | 130 / 38 | 1012.0 |
| 28 / 1200 | WGAX | 28.3 | 93.0 | 190 / 45 | 1006.8 |
| 28 / 2000 | 2CWB5 | 28.1 | 92.7 | 330 / 46 | 1006.0 |
| 29 / 2300 | WFAF | 27.7 | 87.6 | 130 / 41 | 1013.2 |
| 30 / 0300 | WFAF | 28.3 | 88.5 | 110 / 36 | 1016.1 |
| 30 / 1100 | 3FNZ5 | 29.9 | 93.9 | 340 / 40 | 995.3 |
| 30 / 1500 | LAIG7 | 27.5 | 91.7 | 250 / 37 | 1010.0 |

Table 3. Selected surface observations for Harvey, 17 August – 1 September 2017.

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| **Martinique** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Martinique Aimé Césaire International Airport (TFFF) (14.59N 61.00W) | | | 18/1400 | 29 | 44 | | | | |
| **St. Lucia** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Hewanorra International Airport (TLPL) (13.73N 60.95W) | | | 18/1318 | 23 | 43 | | | | |
| George F.L. Charles Airport (TLPC) (14.02N 60.99W) | | | 18/1400 | 18 | 39 | | | | |
| **Offshore Sites** | | | | | | | | | |
| **NOAA Buoys** | | | | | | | | | |
| Corpus Christi, TX (42020) [G] (26.97N 96.69W) | 25/1850 | 980.6 | 25/1850 | 52 [F] (5 m, 10 min) | 64 | | | | |
| Freeport, TX (42019) (27.91N 95.35W) | 28/2350 | 997 | 25/1930 | 35 (5 m, 10 min) | 47 | | | | |
| Galveston, TX (42035) (29.23N 94.41W) | 29/2000 | 995.5 | 29/2230 | 38 (5 m, 10 min) | 52 | | | | |
| TGLO TABS Buoy J (42044) (26.19N 97.05W) | 25/1100 | 1000.2 | 25/1130 | 27 (3.4 m, 10 min) | 34 | | | | |
| TGLO TABS Buoy K (42045) (26.22N 96.50W) | 25/1330 | 990.6 | 25/1400 | 37 (3.4 m, 10 min) | 49 | | | | |
| **Oil Platforms** | | | | | | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Eugene Island 215 (KEIR) (26.19N 97.05W) | 30/0948 | 1002.5 | 30/1230 | 34 (24.7 m) | 41 | 3.1 | 4.68 | | |
| Mississippi Canyon 311a (KMDJ) (26.22N 96.50W) | | | 30/0535 | 36 (90 m) | 48 | | | | |
| **United States** | | | | | | | | | |
| **Alabama** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Lowe Army Heliport (KLOR) (31.33N 85.75W) | | | | | | | | | 4.39 |
| Mobile Downtown Airport (KBFM) (30.63N 88.07W) | | | | | | | | | 4.73 |
| Mobile Regional Airport (KMOB) (30.69N 88.24W) | | | | | | | | | 6.22 |
| **Weatherflow Sites** | | | | | | | | | |
| Orange Beach/Mill Point (XMLP) (30.30N 87.51W) | | | 30/0902 | 23 (5.5 m, 5 min) | 35 | | | | |
| **Other Sites** | | | | | | | | | |
| Ariton 4 W (ARTA1) (31.59N 85.78W) | | | | | | | | | 5.28 |
| Atmore 12 N (ATMA1) (31.17N 87.44W) | | | | | | | | | 4.50 |
| Daleville 2 W (DALA1) (31.34N 85.75W) | | | | | | | | | 5.40 |
| Sellerville 1 E (SLLA1) (31.13N 85.98W) | | | | | | | | | 4.40 |
| Semmes 5 SW (BCDA1) (30.72N 88.30W) | | | | | | | | | 8.04 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Silverhill 3 W (FSHA1) (30.55N 87.8W) | | | | | | | | | 6.20 |
| Skipperville 3 ENE (SKPA1) (31.58N 85.50W) | | | | | | | | | 4.72 |
| **Arkansas** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Monticello Municipal Airport (KLLQ) (33.64N 91.75W) | | | | | | | | | 3.20 |
| Stuttgart Municipal Airport (KSGT) (34.60N 91.57W) | | | | | | | | | 4.31 |
| **Other Sites** | | | | | | | | | |
| Beedeville 4 NE (BDVA4) (35.47N 91.05W) | | | | | | | | | 4.40 |
| **Florida** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Bob Sikes Airport (KCEW) (30.78N 86.52W) | | | | | | | | | 5.69 |
| Destin Executive Airport (KDTS) (30.40N 86.47W) | | | | | | | | | 4.53 |
| Pensacola International Airport (KPNS) (30.47N 87.19W) | | | | | | | | | 7.99 |
| **Other Sites** | | | | | | | | | |
| Chipley (CHPF1) (30.78N 85.48W) | | | | | | | | | 3.55 |
| Geneva 5 ESE (GNEF1) (28.72N 81.04W) | | | | | | | | | 3.57 |
| Milton 7 ESE (MLYF1) (30.57N 86.92W) | | | | | | | | | 4.18 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Oldsmar 2 W (TBFF1) (28.05N 82.71W) | | | | | | | | | 4.99 |
| **Georgia** | | | | | | | | | |
| **Other Sites** | | | | | | | | | |
| Adel 7 W (31.16N 83.54W) | | | | | | | | | 3.02 |
| Donalsonville (DNVG1) (31.03N 84.89W) | | | | | | | | | 3.17 |
| **Kentucky** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Campbell Army Airfield/Fort Campbell (KHOP) (36.67N 87.49W) | | | 01/0725 | 29 (10 m, 2 min) | 41 | | | | 4.40 |
| **Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) Sites** | | | | | | | | | |
| Auburn 0.3 SW (KY-LG-4) (36.86N 86.72W) | | | | | | | | | 8.55 |
| Auburn 2.6 SSW (KY-LG-5) (36.83N 86.74W) | | | | | | | | | 8.76 |
| Bowling Green 1.6 SW (KY-WR-26) (36.98N 86.46W) | | | | | | | | | 8.23 |
| Guthrie 0.8 WNW (KY-WR-28) (36.65N 87.18W) | | | | | | | | | 7.80 |
| Hodgenville 0.1 SSW (KY-AL-17) (37.57N 85.74W) | | | | | | | | | 6.89 |
| Russellville 1.3 NNE (KY-LG-3) (36.86N 86.89W) | | | | | | | | | 8.02 |
| Scottsville 4.9 NE (KY-AL-11) (36.88N 86.17W) | | | | | | | | | 7.65 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Smiths Grove 0.3 SE (KY-WR-26) (37.05N 86.20W) | | | | | | | | | 8.19 |
| Valley Station 1.6 NNE (KY-JF-21) (38.13N 85.85W) | | | | | | | | | 6.52 |
| **Other Sites** | | | | | | | | | |
| Alvaton (ALVK2) (36.90N 86.38W) | | | | | | | | | 10.68 |
| Bowling Green (BWGK2) (37.00N 86.43W) | | | | | | | | | 11.22 |
| Finney (BRRK2) (36.90N 86.13W) | | | | | | | | | 7.58 |
| **Louisiana** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Abbeville/Chris Crusta Memorial Airport (KIYA) (29.98N 92.08W) | 30/1035 | 1001 | 30/2055 | 25 (10 m, 2 min) | 34 | | | | |
| Belle Chasse Naval Air Station (KNBG) (29.82N 90.03W) | 30/1055 | 1006.6 | 30/1955 | 26 (10 m, 2 min) | 36 | | | | |
| Boothville (KBVE) (29.33N 89.40W) | 30/1159 | 1007.8 | 30/1422 | 31 (10 m, 2 min) | 42 | | | | 0.46 |
| Cameron (KCVW) (29.78N 93.30W) | 30/0805 | 992.9 | 30/0735 | 30 (10 m, 2 min) | 42 | | | | |
| De Quincy Industrial Air Park (K5R8) (30.44N 93.47W) | 30/1015 | 994.2 | 30/2035 | 22 (10 m, 2 min) | 34 | | | | |
| Fort Polk (KPOE) (31.04N 93.19W) | 30/1333 | 998.6 | 26/2020 | 25 (10 m, 2 min) | 36 | | | | 15.04 |
| Galliano (KGAO) (29.44N 90.26W) | | | 30/1855 | 24 (10 m, 2 min) | 35 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Lafayette Regional Airport (KLFT) (30.21N 91.98W) | 30/1054 | 1001 | 30/2148 | 26 (10 m, 2 min) | 36 | | | | 7.90 |
| Lake Charles Regional Airport (KLCH) (30.13N 93.23W) | 30/0905 | 993.9 | 30/0932 | 25 (10 m, 2 min) | 39 | | | | 14.52 |
| New Iberia/Acadiana Regional Airport (KARA) (30.03N 91.88W) | 30/1053 | 1001.7 | 30/2100 | 24 (10 m, 2 min) | 35 | | | | 9.12 |
| New Orleans Lakefront Airport (KNEW) (30.04N 90.03W) | 30/1008 | 1005.8 | 30/1551 | 35 (10 m, 2 min) | 49 | | | | 5.33 |
| Port Fourchon (KXPY) | | | 30/1915 | 26 (10 m, 2 min) | 41 | | | | |
| Sulphur/Southland Field Airport (KUXL) (30.13N 93.38W) | 30/0145 | 1001.3 | 28/1235 | 22 (10 m, 2 min) | 34 | | | | |
| **Louisiana State University Coastal Studies Institute Sites** | | | | | | | | | |
| South Pelto Block (SPLL1) (29.20N 89.43W) | | | 30/1700 | 34 (10 m, 8 min) | 41 | | | | |
| **National Ocean Service (NOS) Sites** | | | | | | | | | |
| Amerada Pass (AMRL1 / 8764227) (29.45N 91.34W) | 30/0942 | 1003.2 | 29/0812 | 18 (11m) | 25 | 3.09 | 3.74 | 2.9 | |
| Berwick (TESL1 / 8764044) (29.67N 91.24W) | 30/0948 | 1003.5 | 30/1206 | 25 (12.5m) | 33 | 2.40 | | 1.5 | |
| Bulk Terminal (8767961) (30.19N 93.30W) | | | | | | 3.56 | | 3.2 | |
| Calcasieu Pass (CAPL1 / 8768094) (29.77N 93.34W) | 30/0748 | 992.0 | 28/0554 | 34 (12.3m) | 44 | 2.94 | | 2.8 | |
| Eugene Island (8764314) (29.37N 91.38W) | 30/0948 | 1002.5 | 30/1230 | 35 | 42 | 3.12 | | 2.8 | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Freshwater Canal Locks (FRWL1 / 8766072) (29.55N 92.31W) | 30/0930 | 999.6 | 30/0912 | 31 (19.5m) | 40 | 3.99 | | 3.2 | |
| Grand Isle (GISL1 / 8761724) (29.26N 89.96W) | 30/0848 | 1006.7 | 30/1542 | 23 | 34 (9.3m) | 1.22 | | 1.3 | |
| Lake Charles (LCLL1 / 8767816) (30.22N 93.22W) | 30/0942 | 994.3 | | | | 3.73 | | 3.6 | |
| Port Fourchon, Belle Pass (8762075) (29.11N 90.20W) | | | | | | 1.28 | | 1.3 | |
| **United States Geological Survey Sites** | | | | | | | | | |
| Bayou Grand Caillou (29.38N 90.72W) | | | | | | 1.8 [H] | 3.01 | | |
| Grand Isle (29.27N 89.95W) | | | | | | 1.8 [H] | 3.05 | | |
| Lafitte (29.48N 90.01W) | | | | | | 1.6 [H] | 2.65 | | |
| **United States Army Corps of Engineers Sites** | | | | | | | | | |
| Houma Navigation Canal (29.39N 90.73W) | | | | | | 1.5 [H] | 2.81 | | |
| Mandeville (30.37N,90.09W) | | | | | | 2.5 [H] | 3.49 | | |
| **Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) Sites** | | | | | | | | | |
| Goldonna 1.5 N (LA-NT-5) (32.04N 92.91W) | | | | | | | | | 12.76 |
| Iowa 0.9 ESE (LA-CC-3) (30.23N 93.00W) | | | | | | | | | 16.66 |
| Iowa 9.7 NNW (LA-CC-9) (30.37N 93.07W) | | | | | | | | | 17.44 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Natchitoches 4.8 WNW (LA-NT-3) (31.79N 93.17W) | | | | | | | | | 12.82 |
| Noble 1.8 ESE (LA-SN-7) (31.68N93.32W) | | | | | | | | | 13.10 |
| Pleasant Hill 10.2 SE (LA-SN-3) (31.70N 93.41W) | | | | | | | | | 15.05 |
| Ragley 5 SE (LA-BG-2) (30.47N 93.16W) | | | | | | | | | 16.16 |
| Sulphur 2.2 E (LA-CC-6) (30.23N 93.32W) | | | | | | | | | 13.23 |
| **Weatherflow Sites** | | | | | | | | | |
| Cameron (XCAM) (29.78N 93.29W) | | | 30/1250 | 36 (10.4 m, 1 min) | 43 | | | | |
| Dulac (XDUL) (30.04N 90.02W) | 30/0804 | 1003.8 | 30/1639 | 27 (10.4 m, 1 min) | 36 | | | | |
| Kenner Pontchartrain Causeway (XPTN) (30.20N 90.12W) | | | 30/2007 | 33 (12.5 m, 1 min) | 37 | | | | |
| Mandeville (XMVL) (30.36N 90.09W) | | | 30/1854 | 30 (10.4 m, 1 min) | 35 | | | | |
| New Orleans Lakefront (XLKF) (29.34N 90.73W) | | | 30/1926 | 28 (10.4 m, 1 min) | 49 | | | | |
| Venice East Bay – Tower (XEBT) (29.06N 89.30W) | | | 30/1717 | 29 (15.2 m, 5 min) | 40 | | | | |
| Waggaman Jefferson Parish (XJEF) (29.94N 90.23W) | | | 30/1817 | 22 (10.4m , 1 min) | 35 | | | | |
| **Remote Automated Weather Station (RAWS) Sites** | | | | | | | | | |
| Hackberry (HAKL1) (29.89N 93.40W) | | | 30/1249 | 27 | 42 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Lacassine (30.00N 92.89W) | | | 30/2056 | 27 | 38 | | | | |
| Natchitoches (NATL1) (31.29N 93.11W) | | | | | | | | | 13.04 |
| **Other Sites** | | | | | | | | | |
| Bell City 13 SW (BELL1) (29.97N 93.09W) | | | | | | | | | 22.04 |
| Grand Chenier 9 ESE (GCHL1) (29.73N 92.82W) | | | | | | | | | 15.98 |
| Hackberry 8 SSW (HCKL1) (29.88N 93.42W) | | | | | | | | | 20.71 |
| Lake Arthur (LWRL1) (30.07N 92.68W) | | | | | | | | | 13.30 |
| Lake Charles (LCHL1) (30.25N 93.22W) | | | | | | | | | 17.28 |
| Leesville (LEEL1) (31.13N 93.25W) | | | | | | | | | 16.60 |
| Moss Bluff (MBFL1) (30.30N 93.22W) | | | | | | | | | 18.97 |
| Moss Bluff (MBLL1) (30.30N 93.20W) | | | | | | | | | 20.81 |
| Old Town Bay 6 NE (OTBL1) (30.28N 93.13W) | | | | | | | | | 22.19 |
| Vinton 5 W (NBFL1) (30.18N 93.63W) | | | | | | | | | 23.71 |
| **Mississippi** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Keesler Air Force Base (KBIX) (30.40N 88.92W) | | | | | | | | | 3.69 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| M. Graham Clark Downtown Airport (KPLK) (30.46N 88.53W) | | | | | | | | | 4.58 |
| Natchez-Adams County Airport (KHEZ) (31.61N 91.30W) | | | | | | | | | 4.63 |
| **Weatherflow Sites** | | | | | | | | | |
| Gulfport (XGPT) (30.36N 89.11W) | | | 30/1921 | 32 (10.4 m, 1 min) | 35 | | | | |
| Gulfport/Ship Island (XSHI) (30.23N 88.98W) | | | 30/1854 | 28 (11.9 m, 5 min) | 39 | | | | |
| **Other Sites** | | | | | | | | | |
| Booneville (BOOM6) (34.67N 88.57W) | | | | | | | | | 3.87 |
| Gautier 6 NNW (SHCM6) (30.45N 88.66W) | | | | | | | | | 8.06 |
| Gloster (GLOM6) (31.20N 91.02W) | | | | | | | | | 3.67 |
| Holcut (HCTM6) (34.73N 88.30W) | | | | | | | | | 3.69 |
| Independence 1 W (INDM6) (34.70N 89.82W) | | | | | | | | | 4.77 |
| Necaise 1 N (NNHM6) (30.62N 89.41W) | | | | | | | | | 4.55 |
| New Albany (NABM6) (34.47N 89.00W) | | | | | | | | | 4.76 |
| **North Carolina** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Fayetteville Regional Airport (KFAY) (34.99N 78.88W) | | | | | | | | | 3.02 |
| **Other Sites** | | | | | | | | | |
| Barber 3 S (BBRN7) (35.68N 80.61W) | | | | | | | | | 3.34 |
| Charlotte (MYSN7) (35.46N 80.81W) | | | | | | | | | 3.65 |
| Charlotte 12 N (GILN7) (35.41N 80.85W) | | | | | | | | | 3.36 |
| Clayton (CYNN7) (35.64N 78.46W) | | | | | | | | | 4.31 |
| Davidson 8 SW (CWAN7) (35.43N 80.96W) | | | | | | | | | 3.27 |
| Goldsboro 2 N (GOLN7) (35.42N 77.99W | | | | | | | | | 3.66 |
| Huntersville (COKN7) (35.42N 80.90W) | | | | | | | | | 4.18 |
| Shallote 7 NE (NATN7) (34.05N 78.29W) | | | | | | | | | 3.18 |
| **Tennessee** | | | | | | | | | |
| **International Civil Aviation Organization (ICAO) Sites** | | | | | | | | | |
| Memphis International Airport (KMEM) (35.04N 89.98W) | | | 31/2238 | 32 (10 m, 2 min) | 52 | | | | 4.06 |
| **Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) Sites** | | | | | | | | | |
| Adams 2.9 WSW (TN-RB-18) (36.57N 87.06W) | | | | | | | | | 8.73 |
| Cedar Hill 2.6 N (TN-RB-16) (36.59N 87.00W) | | | | | | | | | 10.67 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Cedar Hill 4.4 NNE (TN-RB-38) (36.61N 86.98W) | | | | | | | | | 9.45 |
| Clarksville 14.4 WSW (TN-MT-73) (36.46N 87.57W) | | | | | | | | | 8.67 |
| Finger 4.1 ENE (TN-MN-3) (35.38N 88.55W) | | | | | | | | | 8.67 |
| Greenbrier 1.4 N (TN-RB-15) (36.44N 86.80W) | | | | | | | | | 10.93 |
| Nashville 4.1 SSW (TN-DV-152) (36.11N 86.81W) | | | | | | | | | 18.20 |
| Pleasant View 2.8 ESE (TN-RB-35) (36.38N 86.99W) | | | | | | | | | 9.18 |
| Sommerville 1.3 E (TN-FY-5) (35.24N 89.33W) | | | | | | | | | 8.63 |
| Springfield 2.9 NNW (TN-RB-6) (36.54N 86.90W) | | | | | | | | | 10.17 |
| Springfield 4.4 SSW (TN-RB-31) (36.44N 86.98W | | | | | | | | | 9.30 |
| **Other Sites** | | | | | | | | | |
| Henderson 1 N (HENT1) (35.45N 88.68W) | | | | | | | | | 11.04 |
| **Texas** | | | | | | | | | |
| **ICAO Sites** | | | | | | | | | |
| Alice International Airport (KALI) (27.74N 98.03W) | 26/0653 | 1000.7 | 26/0853 | 29 (10 m, 2 min) | 41 | | | | 0.33 |
| Angleton/Brazoria County Airport (KLBX) (29.12N 95.47W) | 28/1545 | 1000.3 | 29/1953 | 29 (10 m, 2 min) | 41 | | | | 18.49 |
| Aransas County Airport (KRKP) (28.09N 97.04W) | 26/0153 | 969.8 | 25/2202 | 44 (10 m, 2 min) | 60 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Austin Bergstrom International Airport (KAUS) (30.18N 97.68W) | 27/0753 | 1003.6 | 27/0302 | 39 (10 m, 2 min) | 47 | | | | 10.07 |
| Austin/Camp Mabry (30.32N 97.77W) | 27/0751 | 1005.7 | 27/1729 | 20 (10 m, 2 min) | 39 | | | | 7.97 |
| Bay City Municipal Airport (KBYY) (28.97N 95.86W) | 28/2355 | 999.0 | 28/2355 | 31 (10 m, 2 min) | 40 | | | | |
| Beeville Municipal Airport (KBEA) (28.36N 97.79W) | | | 26/0015 | 30 (10 m, 2 min) | 38 | | | | |
| Brazos 451 Oil Platform (KBQX) (28.49N 95.72W) | 29/0155 | 997.3 | 26/0635 | 46 (24.7 m, 2 min) | 61 | | | | |
| Burnet Municipal Airport (KBMQ) (30.74N 98.23W) | 27/0953 | 1008.9 | 26/1823 | 23 (10 m, 2 min) | 34 | | | | |
| Calhoun County Airport (KPKV) (28.65N 96.68W) | | | 26/0058 | 34 (10 m, 2 min) | 43 | | | | |
| Cleveland Municipal Airport (K6R3 ) (30.35N 95.01W) | 30/1415 | 1004.1 | 30/1615 | 17 (10 m, 2 min) | 47 | | | | 25.76 |
| College Station/Easterwood Field (KCLL) (30.58N 96.37W) | 28/1410 | 1006.4 | 27/2210 | 26 (10 m, 2 min) | 37 | | | | 15.74 |
| Corpus Christi International Airport (KCRP) (27.77N 97.50W) | 25/2351 | 994.5 | 25/2251 | 36 (10 m, 2 min) | 55 | | | | 1.46 |
| Eagle Lake Airport (KELA ) (29.60N 96.32W) | 28/0435 | 1001.7 | 26/1115 | 25 (10 m, 2 min) | 36 | | | | |
| Fredericksburg (KT82) (30.24N 98.91W) | 27/0815 | 1008.2 | 26/2315 | 27 (10 m, 2 min) | 35 | | | | 0.73 |
| Galveston Scholes Field (KGLS) (29.27N 94.87W) | 29/1535 | 1000.7 | 29/2355 | 39 (10 m, 2 min) | 49 | | | | 22.87 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Georgetown (KGTU) (30.69N 97.69W) | 27/1340 | 1009.2 | 27/1340 | 24 (10 m, 2 min) | 35 | | | | 4.59 |
| Giddings (KGYB) (30.17N 96.98W) | 26/2335 | 1001.9 | 27/0455 | 26 (10 m, 2 min) | 38 | | | | 15.77 |
| Gonzales (KT20) (29.52N 97.46W) | 26/1715 | 996.2 | 26/1715 | 30 (10 m, 2 min) | 45 | | | | 13.46 |
| Hondo Municipal Airport (KHDO) (29.36N 99.16W) | 27/0851 | 1005.8 | 27/1559 | 33 (10 m, 2 min) | 44 | | | | |
| Houston Executive Airport (KTME) 29.81N 95.90W) | 28/1335 | 1002.7 | 28/2155 | 29 (10 m, 2 min) | 40 | | | | |
| Houston Hobby Airport (KHOU) (29.65N 95.28W) | 28/1315 | 1002.4 | 29/1853 | 29 (10 m, 2 min) | 42 | | | | 37.01 |
| Houston Sw Airport (KAXH) (29.51N 95.48W) | 28/1335 | 1002 | 26/0615 | 26 (10 m, 2 min) | 37 | | | | |
| Houston/Bush Intercontinental Airport (KIAH) (29.97N 95.35W) | 28/1435 | 1003.4 | 26/1807 | 31 (10 m, 2 min) | 41 | | | | 31.26 |
| Houston/Ellington Field (KEFD) (29.62N 95.17W) | 29/1650 | 1003.3 | 26/1750 | 27 (10 m, 2 min) | 36 | | | | |
| La Grange/Fayette Regional Airport (K3T5) (29.91N 96.95W) | 26/1615 | 1001.8 | 26/1802 | 20 (10 m, 2 min) | 35 | | | | 18.98 |
| Mustang Beach Airport (KRAS) (27.81N 97.09W) | | | 25/1955 | 47 (10 m, 2 min) | 59 | | | | 3.95 |
| Naval Air Station Corpus Christi (KNGP) (27.69N 97.29W) | | 986.1 | 25/2149 | 54 (10 m, 2 min) | 77 | | | | 0 |
| Naval Air Station Kingsville (KNQI) (27.51N 97.81W) | 26/0056 | 999.0 | 25/1956 | 31 (10 m, 2 min) | 42 | | | | 1.93 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| New Braunfels Municipal Airport (29.70N 98.05W) | 26/2251 | 1000.8 | 27/0025 | 38 (10 m, 2 min) | 50 | | | | 7.03 |
| Nueces County Airport (KRBO) (27.78N 97.69W) | | | 26/0315 | 39 (10 m, 2 min) | 51 | | | | |
| Orange County Airport (KORG) (30.07N 93.80W) | 30/0925 | 994.2 | 30/0855 | 26 (10 m, 2 min) | 43 | | | | 36.47 |
| Palacios Municipal Airport (KPSX) (28.72N 96.25W) | 26/0653 | 1000 | 26/1420 | 43 (10 m, 2 min) | 60 | | | | 7.84 |
| Pearland/Clover Field (KLVJ) (29.52N 95.24W) | 28/1320 | 1002.7 | 26/1430 | 29 (10 m, 2 min) | 44 | | | | 34.43 |
| Pleasanton (KPEZ) (28.95N 98.52W) | 27/0955 | 1002.9 | 26/1715 | 26 (10 m, 2 min) | 37 | | | | 0.85 |
| Port Isabel Arpt (KPIL) (26.15N 97.23W) | 25/1253 | 1001.9 | 25/1553 | 24 (10 m, 2 min) | 34 | | | | 0.48 |
| Port San Antonio (KSKF) (29.38N 98.58W) | 27/0730 | 1002.7 | 26/1258 | 26 (10 m, 2 min) | 42 | | | | 0.91 |
| Randolph Air Force Base (KRND) (29.54N 98.28W) | 27/0756 | 1001.3 | 26/1652 | 28 (10 m, 2 min) | 50 | | | | 4.23 |
| Robert Wells Airport (K66R) (29.64N 96.51W) | 28/0255 | 1002.4 | 26/1335 | 24 (10 m, 2 min) | 34 | | | | |
| San Antonio International Airport (KSAT) (29.54N 98.47W) | 27/0751 | 1001.8 | 26/1744 | 30 (10 m, 2 min) | 46 | | | | 1.94 |
| San Antonio Stinson Municipal Airport (KSSF) (29.33N 98.47W) | 27/0753 | 1001.4 | 26/1802 | 26 (10 m, 2 min) | 39 | | | | 1.49 |
| San Marcos (KHYI) (29.90N 97.87W) | 26/2256 | 1002 | 27/0132 | 36 (10 m, 2 min) | 48 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Southeast Texas Regional Airport (KBPT) (29.95N 94.03W) | 30/1053 | 996.5 | 30/1030 | 30 (10 m, 2 min) | 43 | | | | 47.52 |
| Sugarland Regional Airport (KSGR) (29.62N 95.65W) | 28/1320 | 1001.7 | 26/1150 | 38 (10 m, 2 min) | 50 | | | | 22.67 |
| Victoria Regional Airport (KVCT) (28.85N 96.92W) | 26/0451 | 998.3 | 26/0451 | 37 (10 m, 2 min) | 51 | | | | 1.06 |
| **Coastal-Marine Automated Network (C-MAN) Sites** | | | | | | | | | |
| Port Aransas (PTAT2) (27.82N 97.05W) | 26/0200 | 961.7 | 26/0220 | 83 (14.9 m) | 108 | | | | |
| Sabine Pass (SRST2) (29.68N 94.03W) | 30/0800 | 998.3 | 30/0700 | 33 (9.1 m) | 40 | | | | |
| **National Estuarine Research Reserve System Sites** | | | | | | | | | |
| Aransas Ship Channel (MIST2) (27.83N 97.05W) | 26/0115 | 967 | 25/2200 | 57[F] (9.1 m) | | | | | |
| Copano East (MAXT2) (27.13N 97.03W) | 26/0200 | 972 | 26/0200 | 73[F] (7.5 m) | | | | | |
| **National Ocean Service (NOS) Sites** | | | | | | | | | |
| Bob Hall Pier (MQTT2 / 8775870) (27.58N 97.22W) | 26/0112 | 986.3 | 25/2242 | 50 (12.7 m) | 66 | 4.24 | 4.72 | 3.5 | |
| Eagle Point (EPTT2 / 8771013) (29.48N 94.92W) | 29/1106 | 1002.0 | 26/0354 | 36 | 45 | 4.18 | | 3.7 | |
| Freeport (FCGT2 / 8772447) (28.94N 95.30W) | 28/2106 | 999.3 | 26/0930 | 44 | 53 | 3.19 | | 2.5 | |
| Galveston Bay Entrance/North Jetty (GNJT2 / 8771341) (29.68N 94.03W) | 29/1900 | 998.3 | 26/1348 | 46 | 54 | 2.73 | | 2.6 | |
| Galveston Pier 21 (GTOT2 / 8771450) (29.36N 94.72W) | 29/1854 | 998.6 | | | | 2.87 | 3.96 | 2.7 | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Matagorda Bay Entrance Channel (MBET2 / 8773767) (28.643N 96.33W) | 26/0130 | 993.9 | 26/0224 | 58 | 68 | 2.76 | | 2.3 | |
| Morgans Point (MGPT2 / 8770613) (29.68N 94.98W) | 29/1054 | 1002.3 | 26/0048 | 29 | 40 | 4.06 | 4.74 | 3.5 | |
| Port Isabel TX (PTIT2 / 8779770) (26.06N 97.21W) | 25/1154 | 1001.2 | 25/1130 | 21 (11.6 m) | 31 | 1.64 | 1.93 | 1.4 | |
| Rainbow Bridge (8770520) (29.98N 93.88W) | | | | | | 3.38 | | 2.9 | |
| Rockport (RCPT2 / 8774770) (28.02N 97.05W) | 26/0336 | 941.8 | 26/0154 | 59 [F] (7.5 m) | 94 | 1.97 [I] | 3.16 | | |
| Sabine Pass North (SBPT2 / 8770570) (29.73N 93.87W) | 30/0848 | 998.2 | 26/1812 | 33 (7.9 m) | 47 | 3.44 | 4.78 | 3.2 | |
| SPI Brazos Santiago (BZST2 / 8779749) (26.07N 97.15W) | 25/1254 | 1000.1 | 25/1548 | 33 | 40 | 1.67 | | 1.4 | |
| Texas Point (TXPT2 / 8770822) (29.69N 93.84W) | 30/0848 | 995.5 | 29/0800 | 43 (12.5 m) | 53 | 3.26 | | 3.1 | |
| **Remote Automated Weather Station (RAWS) Sites** | | | | | | | | | |
| Aransas Wildlife Refuge (AFWT2) (28.30N 96.82W) | | | 25/2259 | 45 | 94 | | | | |
| Matagorda Island (MIRT2) (28.12N 96.80W) | | | 25/2312 | 44 [F] | 72 | | | | |
| McFadden National Wildlife Refuge (FADT2) (29.71N 94.12W) | | | 29/2035 | 23 | 38 | | | | |
| Victoria (VCRT2) (28.86N 96.92W) | | | 26/1204 | 50 | 72 | | | | |
| Woodville (WVLT2) (30.75N 94.40W) | 30/1104 | 989.8 | 30/1804 | 17 | 34 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| **Texas Coastal Observing Network Sites** | | | | | | | | | |
| Aransas Wildlife Refuge (AWRT2 / 8774230) (28.23N 96.80W) | 26/0424 | 970.5 | 26/0112 | 69 | 92 | 4.80 | | 4.8 | |
| Baffin Bay (BABT2) (27.30N 97.40W) | 25/2306 | 995.5 | 25/2230 | 44 (10 m) | 55 | | | | |
| Copano Bay (CPNT2 / 8774513) (28.11N 97.02W) | 26/0400 | 944.0 | 26/0306 | 79 | 103 | 4.12 | | 4.0 | |
| Galveston Railroad Bridge (GRRT2 / 8771486) (29.30N 94.90W) | 29/1106 | 1000.3 | 29/0254 | 38 | 52 | 3.15 | 3.73 | 2.8 | |
| High Island (HIST2 / 8770808) (29.59N 94.39W) | 29/1842 | 999.8 | 29/1848 | 33 | 41 | 5.13 | | 4.1 | |
| Lynchburg Landing (LYBT2 / 8770733) (29.76N 95.08W) | 28/1042 | 1003.2 | 27/1918 | 26 | 37 | 7.75 | 8.85 | 7.3[J] | |
| Manchester (NCHT2 / 8770777) (29.73N 95.27W) | 28/0900 | 1001.6 | 26/0706 | 24 | 31 | 11.52 | | 10.5[J] | |
| Matagorda City (EMAT2 / 8773146) (28.71N 95.91W) | 28/1718 | 997.3 | 26/0300 | 37 | 48 | 3.33 | | 3.2 | |
| Nueces Bay (NUET2 / 8775244) (27.83N 97.49W) | 26/0254 | 989.3 | 26/0324 | 51 | 65 | | | | |
| Packery Channel (PACT2 / 8775792) (27.63N 97.24W) | 26/0136 | 986.1 | 25/2318 | 58 (10.7 m) | 72 | 4.77 | 5.51 | 4.7 | |
| Port Aransas (RTAT2 / 8775237) (27.84N 97.07W) | 26/0224 | 959.3 | 25/2242 | 50[F] (10.7 m) | 69 | 5.65 | 6.17 | 5.3 | |
| Port Aransas Sentinel (ANPT2 / 8775241) (27.84N 97.04W) | 26/0202 | 964 | 26/0142 | 96[F] (14.2 m) | 115 | 1.63[I] | | | |
| Port Arthur (PORT2 / 8770475) (27.84N 97.04W) | 30/0936 | 996.1 | 30/0124 | 26 (10.7 m) | 36 | 4.20 | | 3.7 | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Port Lavaca (VCAT2 / 8773259) (28.64N 96.61W) | 26/0942 | 993.3 | 26/0806 | 53 | 67 | 7.06 | | 6.7 | |
| Port O'Connor (PCNT2 / 8773701) (28.45N 96.40W) | 26/0354 | 994.2 | 26/1054 | 54 (9 m) | 70 | 3.25 | | 3.0 | |
| Realitos Peninsula (RLIT2 / 8779280) (26.26N 97.28W) | 25/1412 | 1001.6 | 25/1542 | 28 | 36 | | | | |
| Rincon del San Jose (RSJT2 / 8777812) (26.80N 97.47W) | 25/1836 | 999.6 | 25/1836 | 34 (10 m) | 41 | | | | |
| Rollover Pass (RLOT2 / 8770971) (29.52N 94.51W) | 29/1806 | 999.6 | 28/0454 | 37 | 44 | 3.87 | | 3.2 | |
| S Bird Island (IRDT2 / 8776139) (27.48N 97.32W) | 25/2306 | 991.7 | 26/0142 | 47 (4.3 m) | 62 | | | | |
| San Luis Pass (LUIT2 / 8771972) (29.08N 95.12W) | 29/1018 | 1002.9 | 26/0130 | 38 | 59 | 3.22 | | 3.3 | |
| Sargent (SGNT2 / 8772985) (28.77N 95.62W) | 28/2024 | 998.3 | 26/0742 | 43 | 55 | 3.19 | | 3.0 | |
| Seadrift (SDRT2 / 8773037) (28.41N 96.71W) | 26/0606 | 985.5 | 26/0630 | 54 (10.1 m) | 74 | 5.77 | | 5.5 | |
| South Padre Island Coast Guard Station (PCGT2 / 8779748) (26.07N 97.17W) | 25/1300 | 1000.9 | 25/1518 | 32 | 40 | 1.77 | | 1.4 | |
| USS Lexington (TAQT2 / 8775296) (27.82N 97.39W) | 26/0242 | 987.8 | | | | 1.18 | 2.06 | 1.0 | |
| **Weatherflow Sites** | | | | | | | | | |
| Clear Lake Park (XCLP) (29.56N 95.07W) | | | 26/0420 | 29 (9.8 m) | 46 | | | | |
| Corpus Christi (XCRP) (27.59N 97.30W) | 26/0132 | 986 | 26/0304 | 47 (10 m, 1 min) | 65 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Crab Lake (XCRB) (29.46N 94.62W) | | | 29/1843 | 47 (19.8 m) | 53 | | | | |
| Galveston Bay (XGAL) (29.54N 94.91W) | | | 26/0401 | 35 (5.2 m) | 42 | | | | |
| Galveston Fishing Pier (XGPR) (29.24N 94.85W) | | | 25/1836 | 43 (11.6 m) | 50 | | | | |
| Laguna Shores (XLAG) (27.63N 97.29W) | 26/206 | 985.4 | 25/2217 | 52 (10 m, 1 min) | 71 | | | | |
| Levee (XLEV) (29.42N 94.89W) | | | 25/2320 | 38 (8.2 m) | 45 | | | | |
| Matagorda Bay (XMGB) (28.59N 95.98W) | | | 26/0458 | 48 (6.1 m) | 56 | | | | |
| Poenisch Park (XPOE) (27.72N 97.34W) | 26/0220 | 988.4 | 26/0115 | 49 (10 m, 1 min) | 64 | | | | |
| Portland Wildcat (XWLD) (27.86N 97.32W) | 26/0335 | 984.7 | 26/0355 | 48 [F] (5 m, 5 min) | 64 | | | | |
| Seabrook (XSBK) (29.55N 95.02W) | | | 26/0315 | 34 (9.1 m) | 41 | | | | |
| South Padre Island (XPAD) (26.08N 97.17W) | | | 25/1030 | 30 (12.2 m, 5 min) | 38 | | | | |
| South Padre Island SPIW Park (XSPP) (26.16N 97.17W) | | | 25/1120 | 29 (5.5 m, 5 min) | 37 | | | | |
| Surfside Beach (XSRF) (28.92N 95.29W) | | | 25/2206 | 37 (7.6 m) | 50 | | | | |
| Texas City (XTEX) (29.36N 94.95W) | | | 26/0226 | 42 (19.8 m) | 48 | | | | |
| **Texas Tech University Hurricane Research Team StickNet** | | | | | | | | | |
| 0102A (27.88N 97.29W) | | | | 50 (2.25 m, 1 min) | 66 | | | | |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| 0103A (27.91N 97.13W) | | | | 69 (2.25 m, 1 min) | 94 | | | | |
| 0104A (28.11N 97.03W) | | | | 69 [F] (2.25 m, 1 min) | 88 | | | | |
| 0105A (28.34N 96.93W) | | | | 71 (2.25 m, 1 min) | 90 | | | | |
| 0106A (28.44N 96.73W) | | | | 57 (2.25 m, 1 min) | 76 | | | | |
| 0108A (28.03N 97.24W) | | | | 73 (2.25 m, 1 min) | 86 | | | | |
| 0110A (28.41N 96.87W) | | | | 68 (2.25 m, 1 min) | 89 | | | | |
| 0111A (28.66N 96.42W) | | | | 69 (2.25 m, 1 min) | 53 | | | | |
| 0112A (28.59N 96.63W) | | | | 44 (2.25 m, 1 min) | 58 | | | | |
| 0213A (27.70N 97.15W) | | | | 66 (2.25 m, 1 min) | 80 | | | | |
| 0214A (27.59N 97.22W) | | | | 53 (2.25 m, 1 min) | 68 | | | | |
| 0220A (28.16N 97.21W) | | | | 74 [F] (2.25 m, 1 min) | 86 | | | | |
| **Other Sites** | | | | | | | | | |
| Beaumont 4 S (JZHT2) (30.02N 94.14W) | | | | | | | | | 49.06 |
| Beaumont 4 WSW (JZLT2) (30.06N 94.21W) | | | | | | | | | 46.54 |
| Beaumont 4 WSW (JZNT2) (30.04N 94.08W) | | | | | | | | | 46.38 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Bevil Oaks 5 ENE (JYOT2) (30.18N 94.19W) | | | | | | | | | 47.28 |
| Brazos Santiago Pass (BRZT2) (26.07N 97.15W) | 25/1254 | 1000.1 | 25/1548 | 32 (10 m, 6 min) | 38 | | | | |
| Central Gardens 5 NW (JZJT2) (30.06N 94.21W) | | | | | | | | | 46.54 |
| China 2 S (JZTT2) (30.02N 94.33W) | | | | | | | | | 47.44 |
| Clear Lake (29.56N 95.14W) | | | | | | | | | 48.14 |
| Coleto Creek (CKDT2) (28.73N 97.17W) | | | | | 77 | | | | 9.42 |
| Copano Bay Causeway Park | 26/0356 | 944.7 | | | | | | | |
| Ellington Field 2 E (29.60N 95.12W) | | | | | | | | | 52.00 |
| Fannet 5 WNW (JZVT2) (29.95N 94.33W) | | | | | | | | | 45.00 |
| Fannett 1 NE (JZPT2) (29.93N 94.24W) | | | | | | | | | 49.25 |
| Friendswood (29.05N 95.20W) | | | | | | | | | 56.00 |
| Friendswood (29.74N 95.57W) | | | | | | | | | 54.00 |
| Friendswood 2 E (29.50N 95.16W) | | | | | | | | | 47.40 |
| Friendswood 2 NNW (29.54N 95.22W) | | | | | | | | | 50.04 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Goliad 10 S (KTXGOLIA4) (28.52N 97.41W) | | | | | 54 [F] | | | | 22.68 |
| GWRT2 (28.36N 98.12W) | | | 26/1406 | 21 | 35 | | | | |
| Hamshire 5 SSW (JYST2) (29.79N 94.34W) | | | | | | | | | 45.79 |
| Highlands 2 SSE (BATT2) (29.79N 95.04W) | | | | | | | | | 45.10 |
| Horsepen Creek @ Bay Area Boulevard (29.58N 95.10W) | | | | | | | | | 45.68 |
| Johnson Space Center Building B30 (29.55N 95.09W) | | | 26/2355 | (12.2 m) | 47 | | | | |
| KTXCUERO1 (29.15N 97.30W) | 26/1435 | 992.6 | 26/1415 | 23 | 36 | | | | |
| KTXCUERO3 (29.15N 97.30W) | 26/1540 | 989.2 | | | | | | | |
| KTXSMILE2 (29.29N 97.57W) | | | | 40 | 50 | | | | |
| KTXSMILE3 (29.12N 97.62W) | | | 26/1516 | 27 | 44 | | | | |
| KTXYORK4 (29.03N 97.53W) | 26/1647 | 991.2 | 26/1500 | 21 | 35 | | | | |
| KTXYORK6 (28.91N 97.50W) | | | | 40 | 42 | | | | |
| League City (DW6282) (29.50N 95.10W) | | | | | | | | | 45.66 |
| League City 3 S (29.43N 95.11W) | | | | | | | | | 52.87 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| League City 3 W (29.48W 95.16W) | | | | | | | | | 45.34 |
| League City 4 S (29.42N 95.11W) | | | | | | | | | 51.62 |
| Liberty 2 WSW (LBYT2) (30.06N 94.82W) | | | | | | | | | 49.39 |
| Nassau Bay 2 SSE (29.51N 95.08W) | | | | | | | | | 47.86 |
| Port Arthur 18 WSW (JYHT2) (29.79N 94.21W) | | | | | | | | | 47.99 |
| Port Lavaca U. Florida Research Tower (FCMP T3) (28.61N 96.63W) | | | 26/0438 | 43 (10 m, 1 min) | 44 | | | | |
| Rockport (ICyclone) (28.058N 97.041W) | 26/0331 | 940.8 | | | | | | | |
| Rockport Doppler on Wheels Anemometer (NSFDOW) (28.08N 97.04W) | | | | 90 (10 m, 1 min) | 126 | | | | |
| Rockport U. Florida Research Tower (FCMP T2) (28.08N 97.05W) | 26/0402 | 941.3 | 26/0252 | 88 (10 m, 1 min) | 122 | | | | |
| Santa Fe 3 ENE (29.39N 95.05W) | | | | | | | | | 54.77 |
| South Padre Island (SPIT2) (26.06N 97.17W) | 25/1300 | 1000.9 | 25/1518 | 32 (10 m, 6 min) | 40 | | | | 2.40 |
| Texas A&M Corpus Christi (27.71N 97.32W) | 26/0153 | 985 | | | 75 | | | | |
| Victoria (TXVC-4) (28.52N 97.41W) | 26/1203 | 984.4 | | | 74 | | | | 14.29 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Webster 2 NW (29.55N 95.14W) | | | | | | | | | 52.30 |
| Webster 2 S (29.51N 95.12W) | | | | | | | | | 48.20 |
| **Community Collaborative Rain, Hail and Snow Network (CoCoRaHS) Sites** | | | | | | | | | |
| Beaumont 4.6 S (TX-JJ-11) (30.02N 94.16W) | | | | | | | | | 45.50 |
| Dayton 0.2 E (TX-LR-14) (30.05N 94.89W) | | | | | | | | | 49.31 |
| Pasadena 4.4 WSW (TX-HRR-93) (29.68N 95.22W) | | | | | | | | | 45.74 |
| Santa Fe 0.7 S (TX-GV-60) (29.37N 95.10W) | | | | | | | | | 46.70 |
| **National Severe Storms Laboratory (NSSL) Probes** | | | | | | | | | |
| Taft (NSSL Probe) (28.04N 97.33W) | | | 26/0410 | 65 (3.4 m, 1 min) | 82 | | | | |
| Woodsboro (NSSL Probe) (28.22N 97.35W) | | | 26/0641 | 60 (3.4 m, 1 min) | 76 | | | | |
| **Center for Severe Weather Research (CWSR) Probes** | | | | | | | | | |
| Rockport (Pod B) (28.08N 97.04W) | | | 26/0227 | 50[F] (1 m, 1 min) | 68 | | | | |
| Rockport (Pod C) (28.09N 97.04W) | | | 26/0139 | 48[F] (1 m, 1 min) | 67 | | | | |
| Rockport (Pod D) (28.11N 97.03W) | | | 26/0138 | 64[F] (1 m, 1 min) | 86 | | | | |
| **Jefferson County Drainage District Rain Gauges** | | | | | | | | | |
| Boondocks Road @ Taylors Bayou, South Fork (6400) (29.85N 94.23W) | | | | | | | | | 47.99 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| Craigen Road @ Taylors Bayou D-500 (5620) (29.88N 94.26W) | | | | | | | | | 47.28 |
| East Bay Bayou @ Skillern Tract (5050) (29.63N 94.41W) | | | | | | | | | 47.44 |
| Frint Road Willow Marsh Bayou (2900) (30.00N 94.16W) | | | | | | | | | 46.38 |
| Glenbrook Drive @ Green Acres / Ditch 407 (3200) (29.94N 94.23W) | | | | | | | | | 49.25 |
| Groves 1.3 N (8906) (29.96N 93.92W) | | | | | | | | | 60.54 |
| Highland Ave @ Ditch 104 (2500) (30.03N 94.08W) | | | | | | | | | 46.50 |
| Landis Drive @ Ditch 202B (2700) (30.07N 94.20W) | | | | | | | | | 46.57 |
| Mayhaw Bayou @ Englin Road (7200) (29.79N 94.34W) | | | | | | | | | 45.79 |
| Nederland 1.5 SW (8920) (29.95N 94.01W) | | | | | | | | | 60.58[K] |
| Pine Tree Ditch 601 South China Road (6200) (29.97N 94.34W) | | | | | | | | | 45.00 |
| Pipkin Ranch @ Willow Slough Ditch 550 (6720) (29.77N 94.20W) | | | | | | | | | 45.12 |
| Port Arthur 6.4 WNW (8918) (29.93N 94.03W) | | | | | | | | | 45.26 |
| Rush Ditch @ Hwy 1663 (6350) (29.86N 94.45W) | | | | | | | | | 45.20 |

| Location | Minimum Sea Level Pressure | | Maximum Surface Wind Speed | | | Storm surge (ft)[C] | Storm tide (ft)[D] | Estimated Inundation (ft)[E] | Total rain (in) |
|---|---|---|---|---|---|---|---|---|---|
| | Date/ time (UTC) | Press. (mb) | Date/ time (UTC)[A] | Sustained (kt)[B] | Gust (kt) | | | | |
| South China Road Ditch 608 (5200) (30.03N 94.33W) | | | | | | | | | 47.44 |
| State Highway 124 @ Hillebrandt Bayou (2300) (30.04N 94.15W) | | | | | | | | | 49.06 |
| State Hwy 365 @ Green Pond Gully (5400) (29.94N 94.33W) | | | | | | | | | 45.00 |
| Winne Wetlands @ Mayhaw Bayou (5250) (29.80N 94.36W) | | | | | | | | | 47.52 |
| **Earth Networks Mesonet Sites** | | | | | | | | | |
| Corpus Christi KRIS TV (KRIST) (27.79N 97.40W) | | | 26/0255 | 32 [F] (10.6 m, 2 min) | 63 | | | | |
| Rockport Texas Maritime Museum (RCKPR) (28.03N 97.05W) | | | 26/2335 | 41 [F] (7.9 m, 2 min) | 67 | | | | |
| Seadrift DOW Chemical (SDRFT) (28.52N 96.77) | | | 26/1125 | 46 [F] (10.6 m, 2 min) | 78 | | | | |

[A] Date/time is for sustained wind when both sustained and gust are listed.
[B] Except as noted, sustained wind averaging periods for C-MAN and land-based reports are 2 min; buoy averaging periods are 8 min.
[C] Storm surge is water height above normal astronomical tide level.
[D] For most locations, storm tide is water height above the North American Vertical Datum of 1988 (NAVD88).
[E] Estimated inundation is the maximum height of water above ground. For NOS tide gauges, the height of the water above Mean Higher High Water (MHHW) is used as a proxy for inundation.
[E] Estimated inundation is the maximum height of water above ground. For NOS tide gauges, the height of the water above Mean Higher High Water (MHHW) is used as a proxy for inundation.
[F] Anemometer damaged or data recording otherwise interrupted and likely did not record maximum winds.
[G] Station 42020 went adrift on 8/25 around 1800 UTC and stopped reporting at that time.
[H] Surge is estimated using a pre-storm baseline for USCOE and USGS gauges
[I] Sensor damaged or destroyed and likely did not record maximum water level
[J] Significantly affected by excessive fresh water rainfall runoff
[K] Preliminary highest tropical cyclone storm total rainfall in U.S. history

Table 4. Direct deaths by county in Texas associated with Harvey.

| County | Direct Deaths |
|---|---|
| Harris | 36 |
| Orange | 9 |
| Jefferson | 5 |
| Galveston | 3 |
| Montgomery | 3 |
| San Jacinto | 3 |
| Ft. Bend | 3 |
| Jasper | 2 |
| Newton | 2 |
| Hardin | 1 |
| Walker | 1 |
| Total | 68 |

Table 5a. Number of hours in advance of formation of Harvey east of the Lesser Antilles associated with the first NHC Tropical Weather Outlook forecast in the indicated likelihood category. Note that the timings for the "Low" category do not include forecasts of a 0% chance of genesis.

| | **Hours Before Genesis** | |
|---|---|---|
| | **48-Hour Outlook** | **120-Hour Outlook** |
| Low (<40%) | 84 | 96 |
| Medium (40%-60%) | 12 | 72 |
| High (>60%) | | |

Table 5b. Number of hours in advance of reformation of Harvey in the Gulf of Mexico with the first NHC Tropical Weather Outlook forecast in the indicated likelihood category. Note that the timings for the "Low" category do not include forecasts of a 0% chance of genesis.

| | **Hours Before Genesis** | |
|---|---|---|
| | **48-Hour Outlook** | **120-Hour Outlook** |
| Low (<40%) | 78 | 78 |
| Medium (40%-60%) | 72 | 78 |
| High (>60%) | 42 | 66 |

Table 6a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) track forecast errors (n mi) for Harvey. Mean errors for the previous 5-yr period are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

| | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | **18.8** | **28.8** | **38.9** | **49.7** | **81.2** | **124.5** | **168.7** |
| OCD5 | 35.6 | 68.8 | 112.1 | 157.1 | 239.5 | 305.3 | 350.8 |
| Forecasts | 38 | 36 | 32 | 28 | 23 | 20 | 20 |
| OFCL (2012-16) | 24.9 | 39.6 | 54.0 | 71.3 | 105.8 | 155.4 | 208.9 |
| OCD5 (2012-16) | 47.3 | 103.9 | 167.8 | 230.3 | 343.1 | 442.6 | 531.0 |

Table 6b. Homogeneous comparison of selected track forecast guidance models (in n mi) for Harvey. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 6a due to the homogeneity requirement.

| Model ID | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | 16.7 | 26.8 | 39.5 | 49.3 | 87.3 | 139.2 | 186.1 |
| OCD5 | 33.9 | 65.6 | 104.4 | 148.1 | 238.9 | 325.5 | 370.5 |
| GFSI | 21.9 | 36.7 | 55.7 | 74.0 | 131.5 | 216.7 | 266.8 |
| AEMI | 22.2 | 37.4 | 57.5 | 73.0 | 124.2 | 175.8 | 224.1 |
| HWFI | 17.7 | 32.2 | 52.5 | 76.4 | 130.2 | 194.5 | 226.1 |
| EGRI | 19.3 | 28.0 | **35.3** | **41.8** | **76.0** | 147.2 | 244.3 |
| EMXI | 22.3 | 35.3 | 47.3 | 56.0 | **82.4** | **133.1** | 212.4 |
| CMCI | 22.8 | 35.8 | 54.8 | 70.1 | 94.5 | **132.4** | **157.8** |
| NVGI | 27.9 | 47.4 | 66.7 | 90.2 | 131.3 | 169.1 | 199.8 |
| CTCI | 17.4 | **26.0** | 40.3 | 51.5 | **71.8** | **122.9** | 193.1 |
| TVCN | **16.4** | **23.8** | **35.0** | **43.2** | **79.2** | **135.1** | **179.4** |
| TVCX | 17.0 | **24.7** | **36.7** | **43.5** | **77.7** | **131.8** | **181.2** |
| HCCA | 17.4 | 28.1 | 42.2 | 53.3 | 97.3 | **138.3** | **178.7** |
| GFEX | 21.1 | 33.8 | 50.0 | 61.3 | 102.0 | 169.7 | 226.3 |
| FSSE | 19.8 | 31.2 | 46.2 | 57.2 | 95.4 | 147.5 | 207.4 |
| TABD | 33.9 | 69.3 | 100.4 | 129.6 | 152.0 | 259.1 | 341.4 |
| TABM | 26.3 | 54.0 | 78.8 | 83.0 | 148.6 | 233.2 | 303.0 |
| TABS | 42.2 | 84.5 | 87.6 | 69.8 | 169.3 | 211.4 | 293.2 |
| Forecasts | 28 | 26 | 24 | 23 | 19 | 17 | 16 |

Table 7a. NHC official (OFCL) and climatology-persistence skill baseline (OCD5) intensity forecast errors (kt) for Harvey. Mean errors for the previous 5-yr period are shown for comparison. Official errors that are smaller than the 5-yr means are shown in boldface type.

| | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | 5.8 | 8.9 | 12.0 | 15.0 | **6.5** | **3.5** | **6.3** |
| OCD5 | 6.7 | 11.5 | 14.9 | 16.9 | 11.5 | 10.2 | 13.8 |
| Forecasts | 38 | 36 | 32 | 28 | 23 | 20 | 20 |
| OFCL (2012-16) | 5.5 | 8.2 | 10.5 | 12.0 | 13.4 | 14.0 | 14.5 |
| OCD5 (2012-16) | 7.1 | 10.5 | 13.0 | 15.1 | 17.4 | 18.2 | 20.6 |

Table 7b. Homogeneous comparison of selected intensity forecast guidance models (in kt) for Harvey. Errors smaller than the NHC official forecast are shown in boldface type. The number of official forecasts shown here will generally be smaller than that shown in Table 7a due to the homogeneity requirement.

| Model ID | Forecast Period (h) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 12 | 24 | 36 | 48 | 72 | 96 | 120 |
| OFCL | 5.0 | 7.2 | 9.8 | 11.7 | 6.3 | 4.1 | 5.9 |
| OCD5 | 5.6 | 10.1 | 12.1 | 12.5 | 10.8 | 9.6 | 14.6 |
| HWFI | 6.3 | 8.0 | **8.8** | **7.5** | 7.3 | 8.7 | 11.6 |
| DSHP | 5.1 | 7.5 | **8.9** | **7.8** | 9.6 | 10.2 | 8.8 |
| LGEM | 5.1 | 7.2 | **9.1** | **8.9** | 9.1 | 9.2 | 7.9 |
| ICON | 5.1 | **6.3** | **7.9** | **7.6** | 8.4 | 9.2 | 8.1 |
| IVCN | 5.2 | **6.1** | **7.0** | **6.7** | 6.7 | 7.6 | 7.4 |
| HCCA | 5.1 | **6.0** | **7.6** | **7.7** | 8.5 | 9.4 | 8.8 |
| FSSE | 5.5 | **6.6** | **8.1** | **8.5** | 11.5 | 10.9 | 7.6 |
| GFSI | 7.4 | 8.6 | **7.9** | **8.9** | **5.6** | 5.6 | 10.4 |
| EMXI | 8.5 | 12.6 | 16.7 | 18.6 | 23.2 | 27.9 | 32.1 |
| Forecasts | 32 | 30 | 27 | 23 | 19 | 17 | 16 |

Table 8. Wind watch and warning summary for Harvey, 17 August – 1 September 2017.

| Date/Time (UTC) | Action | Location |
|---|---|---|
| 17 / 1500 | Tropical Storm Watch issued | Dominica |
| 17 / 1500 | Tropical Storm Warning issued | Martinique, St. Lucia, Barbados, St. Vincent and the Grenadines |
| 18 / 1200 | Tropical Storm Warning discontinued | Barbados |
| 18 / 1800 | Tropical Storm Watch discontinued | All |
| 18 / 1800 | Tropical Storm Warning discontinued | All |
| 23 / 1500 | Tropical Storm Watch issued | Mouth of the Rio Grande to Port Mansfield Texas |
| 23 / 1500 | Tropical Storm Watch issued | San Luis Pass Texas to High Island |
| 23 / 1500 | Tropical Storm Watch issued | Boca de Catan Mexico to Mouth of the Rio Grande |
| 23 / 1500 | Hurricane Watch issued | Port Mansfield to San Luis Pass Texas |
| 24 / 0900 | Tropical Storm Watch changed to Tropical Storm Warning | Mouth of the Rio Grande to Port Mansfield |
| 24 / 0900 | Hurricane Watch issued | Mouth of the Rio Grande to Port Mansfield |
| 24 / 0900 | Tropical Storm Watch discontinued | San Luis Pass to High Island |
| 24 / 0900 | Tropical Storm Warning issued | Matagorda to High Island |
| 24 / 0900 | Hurricane Warning issued | Port Mansfield to Matagorda |
| 24 / 2100 | Tropical Storm Warning modified to | Sargent to High Island |

| | | |
|---|---|---|
| 24 / 2100 | Hurricane Warning modified to | Port Mansfield to Sargent |
| 25 / 1500 | Hurricane Watch changed to Tropical Storm Warning | Mouth of the Rio Grande to Port Mansfield |
| 25 / 2100 | Tropical Storm Watch discontinued | All |
| 25 / 2100 | Tropical Storm Warning discontinued | Mouth of the Rio Grande to Port Mansfield |
| 26 / 0900 | Tropical Storm Warning modified to | Port O'Connor to High Island |
| 26 / 0900 | Hurricane Warning discontinued | Port Mansfield to Sargent |
| 26 / 1500 | Tropical Storm Warning modified to | Baffin Bay to High Island |
| 26 / 1500 | Hurricane Warning discontinued | All |
| 27 / 0300 | Tropical Storm Warning modified to | Baffin Bay to Sargent |
| 27 / 0900 | Tropical Storm Warning modified to | Port O'Connor to Sargent |
| 27 / 2100 | Tropical Storm Watch issued | Sargent to San Luis Pass |
| 28 / 0300 | Tropical Storm Watch discontinued | All |
| 28 / 0300 | Tropical Storm Warning discontinued | Port O'Connor to Sargent |
| 28 / 0300 | Tropical Storm Warning issued | Mesquite Bay to High Island |
| 28 / 1500 | Tropical Storm Watch issued | Cameron to Intracoastal City Louisiana |
| 28 / 1500 | Tropical Storm Warning modified to | Mesquite Bay to Cameron |
| 28 / 2100 | Tropical Storm Watch discontinued | All |
| 28 / 2100 | Tropical Storm Warning modified to | Mesquite Bay to Intracoastal City |
| 29 / 1500 | Tropical Storm Watch issued | Morgan City to Grand Isle |

| | | |
|---|---|---|
| 29 / 1500 | Tropical Storm Warning discontinued | Mesquite Bay to Intracoastal City |
| 29 / 1500 | Tropical Storm Warning modified to | Port O'Connor to Morgan City |
| 30 / 0300 | Tropical Storm Watch discontinued | All |
| 30 / 0300 | Tropical Storm Warning discontinued | Port O'Connor to Morgan City |
| 30 / 0300 | Tropical Storm Warning modified to | Freeport to Grand Isle |
| 30 / 0900 | Tropical Storm Warning modified to | High Island to Grand Isle |
| 30 / 1200 | Tropical Storm Warning modified to | Freeport to Grand Isle |
| 30 / 1800 | Tropical Storm Warning modified to | Sabine Pass to Grand Isle |
| 31 / 0000 | Tropical Storm Warning discontinued | All |

Table 9. United States Storm Surge Watch and Warning summary for Harvey.

| Date/Time (UTC) | Action | Location |
|---|---|---|
| 23 / 1500 | Storm Surge Watch issued | Port Mansfield to High Island, Texas |
| 24 / 0900 | Storm Surge Warning issued | Port Mansfield to San Luis Pass |
| 24 / 0900 | Storm Surge Watch issued | South of Port Mansfield to the Mouth of the Rio Grande |
| 24 / 1800 | Storm Surge Warning issued | North San Luis Pass to High Island |
| 25 / 2100 | Storm Surge Watch discontinued | South of Port Mansfield to the Mouth of the Rio Grande |
| 26 / 0900 | Storm Surge Warning discontinued | South of Baffin Bay to Port Mansfield |
| 26 / 1500 | Storm Surge Warning discontinued | South of Port Aransas to Baffin Bay |
| 27 / 0300 | Storm Surge Warning discontinued | All |
| 28 / 2100 | Storm Surge Watch issued | Port Bolivar Texas to Morgan City Louisiana |
| 29 / 2100 | Storm Surge Warning issued | Holly Beach to Morgan City |
| 30 / 0900 | Storm Surge Watch discontinued | West of High Island to Port Bolivar |
| 30 / 1500 | Storm Surge Watch discontinued | West of Sabine Pass to High Island |
| 30 / 2100 | Storm Surge Watch / Warning discontinued | All |

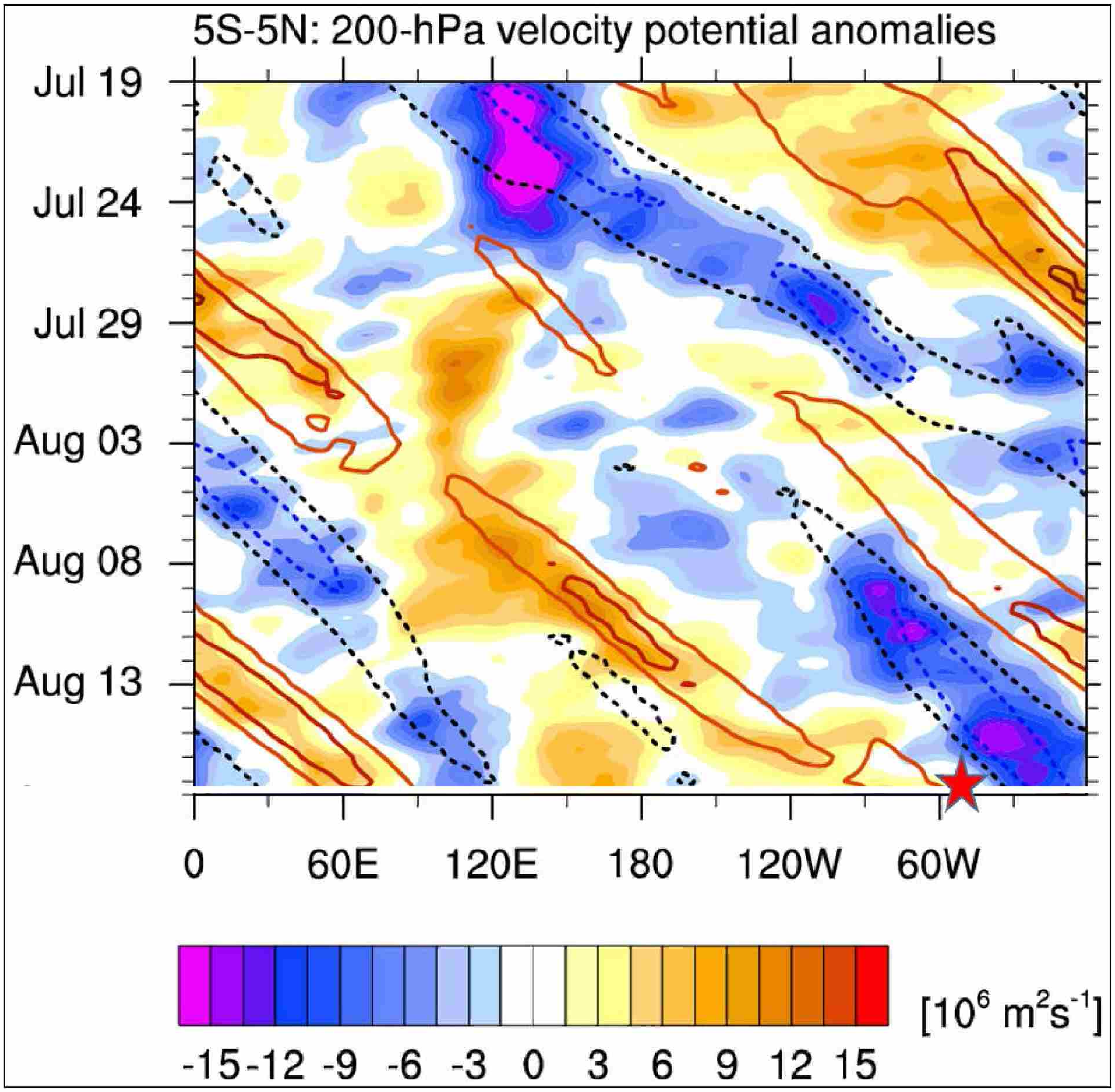


Figure 1. Velocity potential anomalies at 200 mb (VP200) from 5°N-5°S (shaded, x $10^6$ $m^2$ $s^{-1}$). The shading shows unfiltered VP200 anomalies where negative (positive) values represent mass divergence (convergence). Red contours show CCKW-filtered VP200 anomalies; dashed lines represent upper-level divergence (convectively active). The contour interval begins at 1 standard deviation and contours indicate a 0.5 standard deviation increment thereafter. The red star is the genesis point of Harvey. Figure adapted from Michael Ventrice, IBM/The Weather Channel in collaboration with the University of Albany, Albany NY.

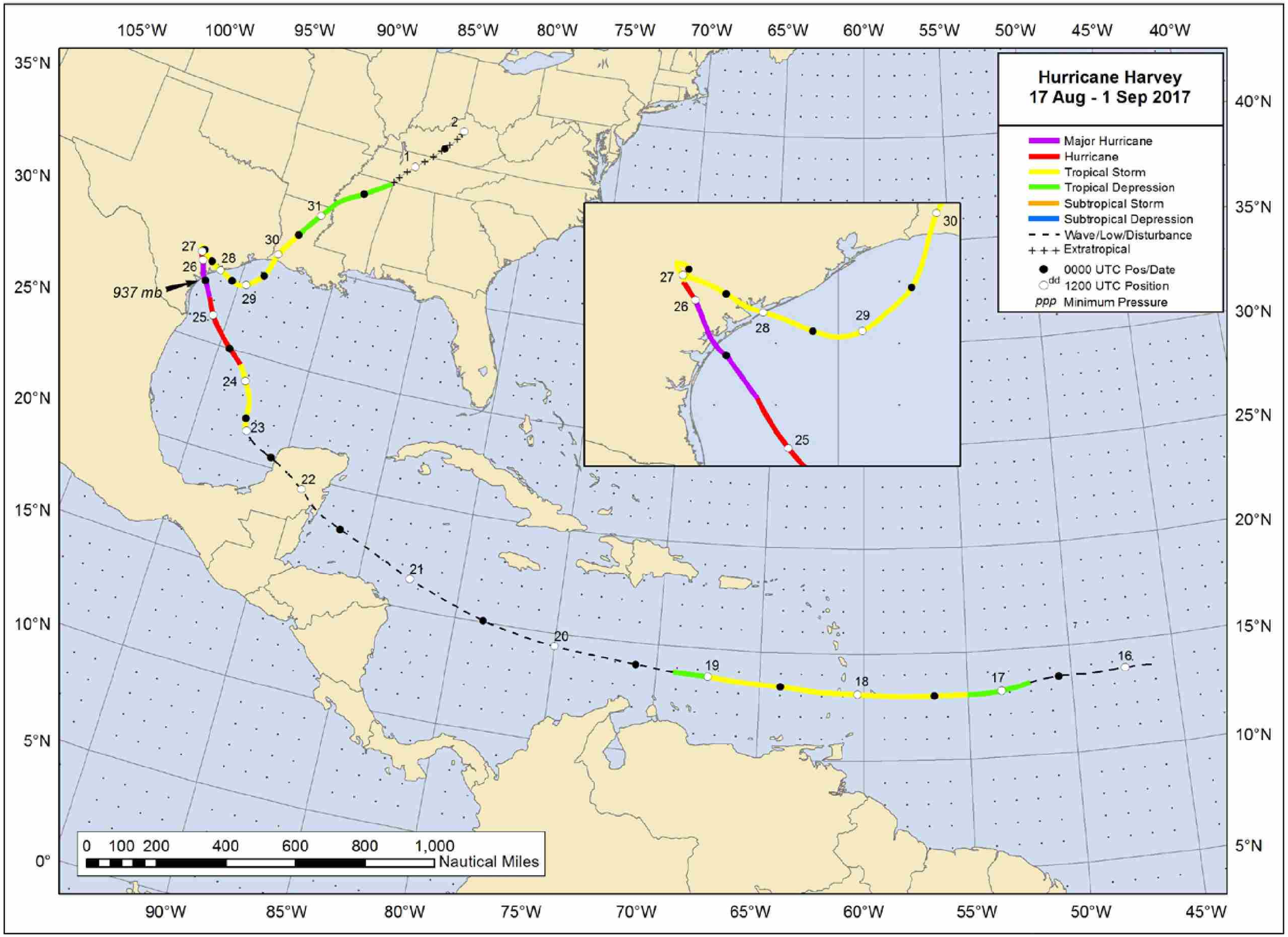


Figure 2. Best track positions for Hurricane Harvey, 17 August – 1 September 2017.

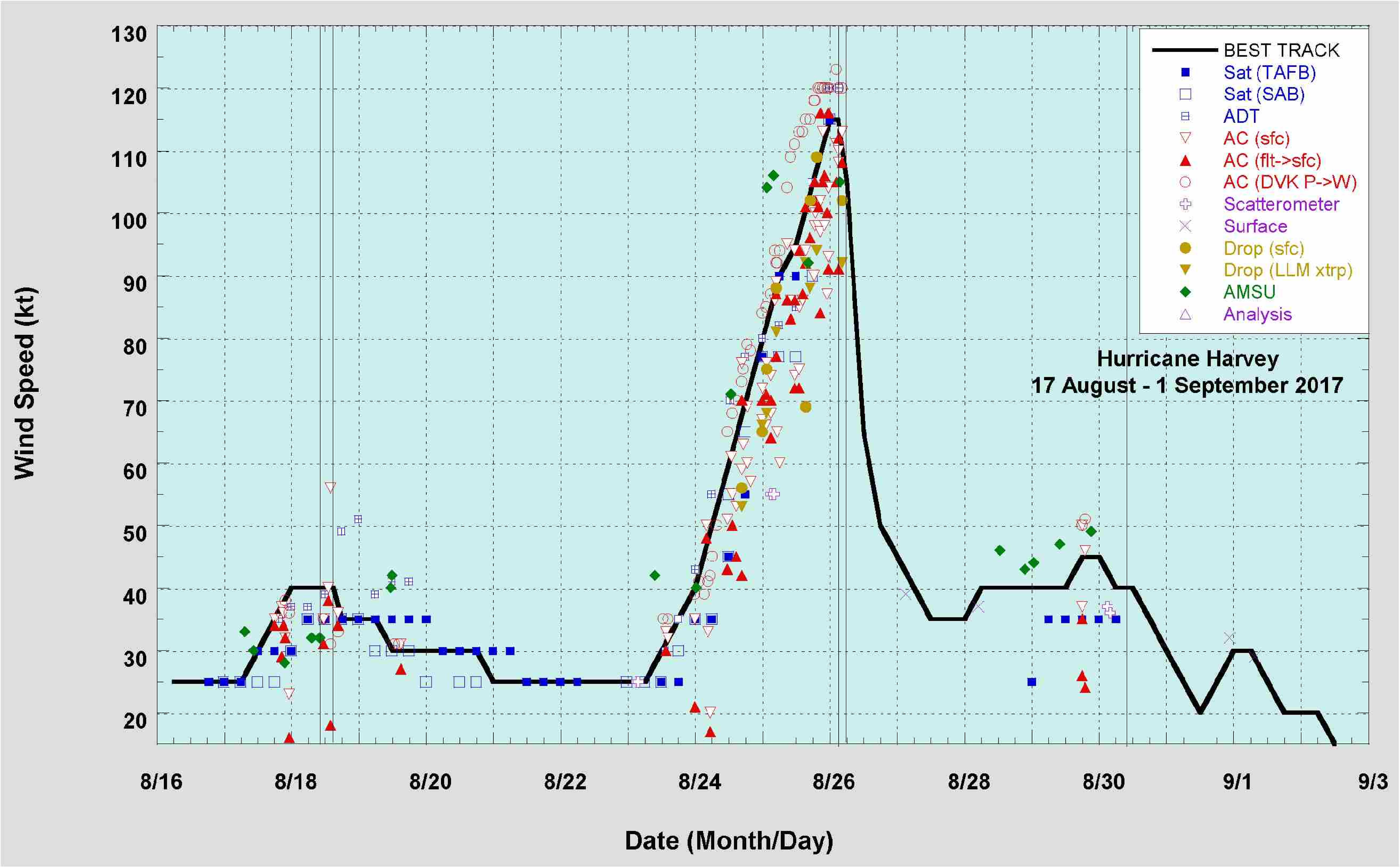


Figure 3. Selected wind observations and best track maximum sustained surface wind speed curve for Hurricane Harvey, 17 August – 1 September. Dropwindsonde observations include actual 10 m winds (sfc), as well as surface estimates derived from the mean wind over the lowest 150 m of the wind sounding (LLM). Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. AMSU intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies technique. Dashed vertical lines correspond to 0000 UTC, and solid vertical lines correspond to landfall.

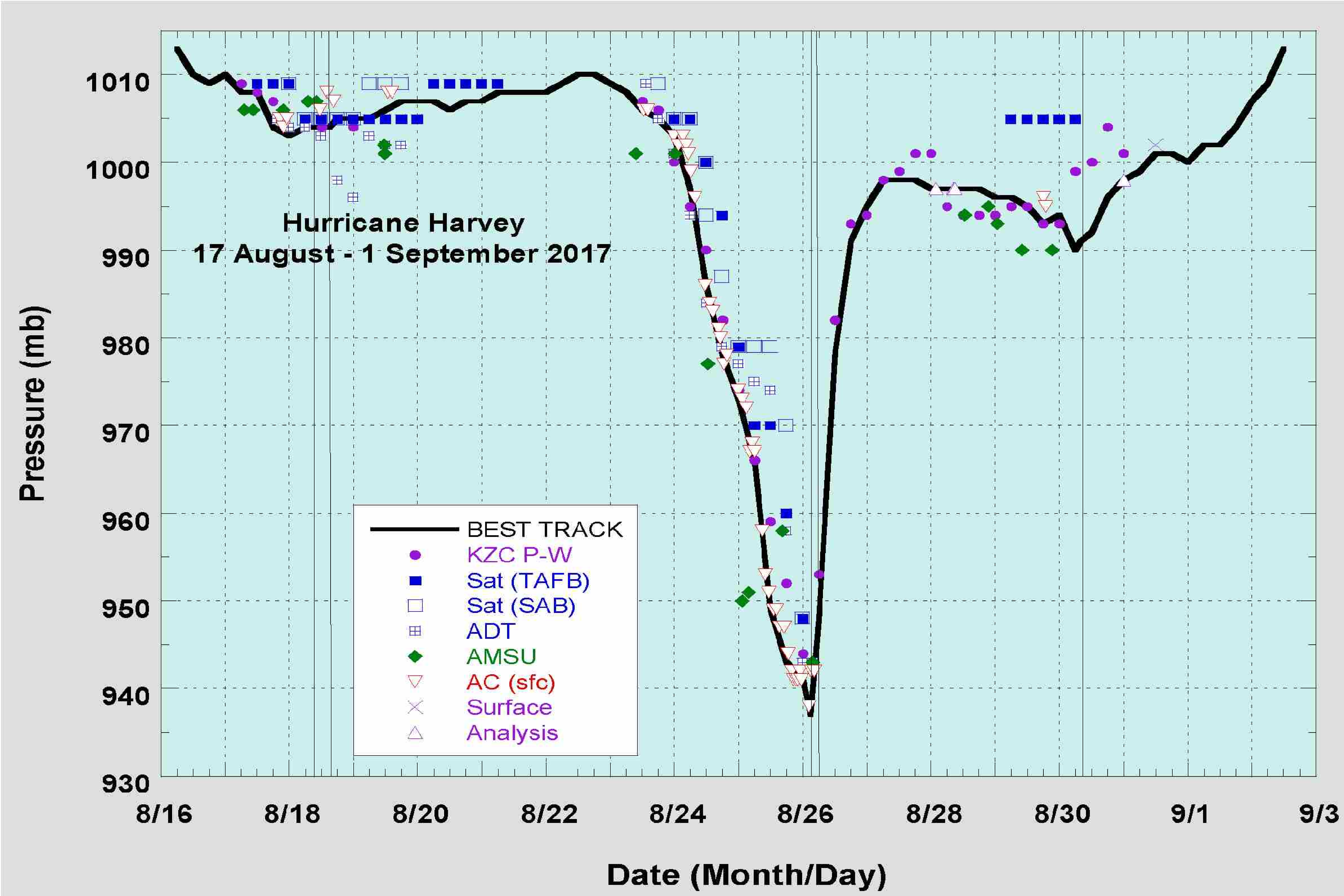


Figure 4. Selected pressure observations and best track minimum central pressure curve for Hurricane Harvey, 17 August – 1 September. Advanced Dvorak Technique estimates represent the Current Intensity at the nominal observation time. AMSU intensity estimates are from the Cooperative Institute for Meteorological Satellite Studies technique. KZC P-W refers to pressure estimates derived using the Knaff-Zehr-Courtney pressure-wind relationship. Dashed vertical lines correspond to 0000 UTC, and solid vertical lines correspond to landfall.

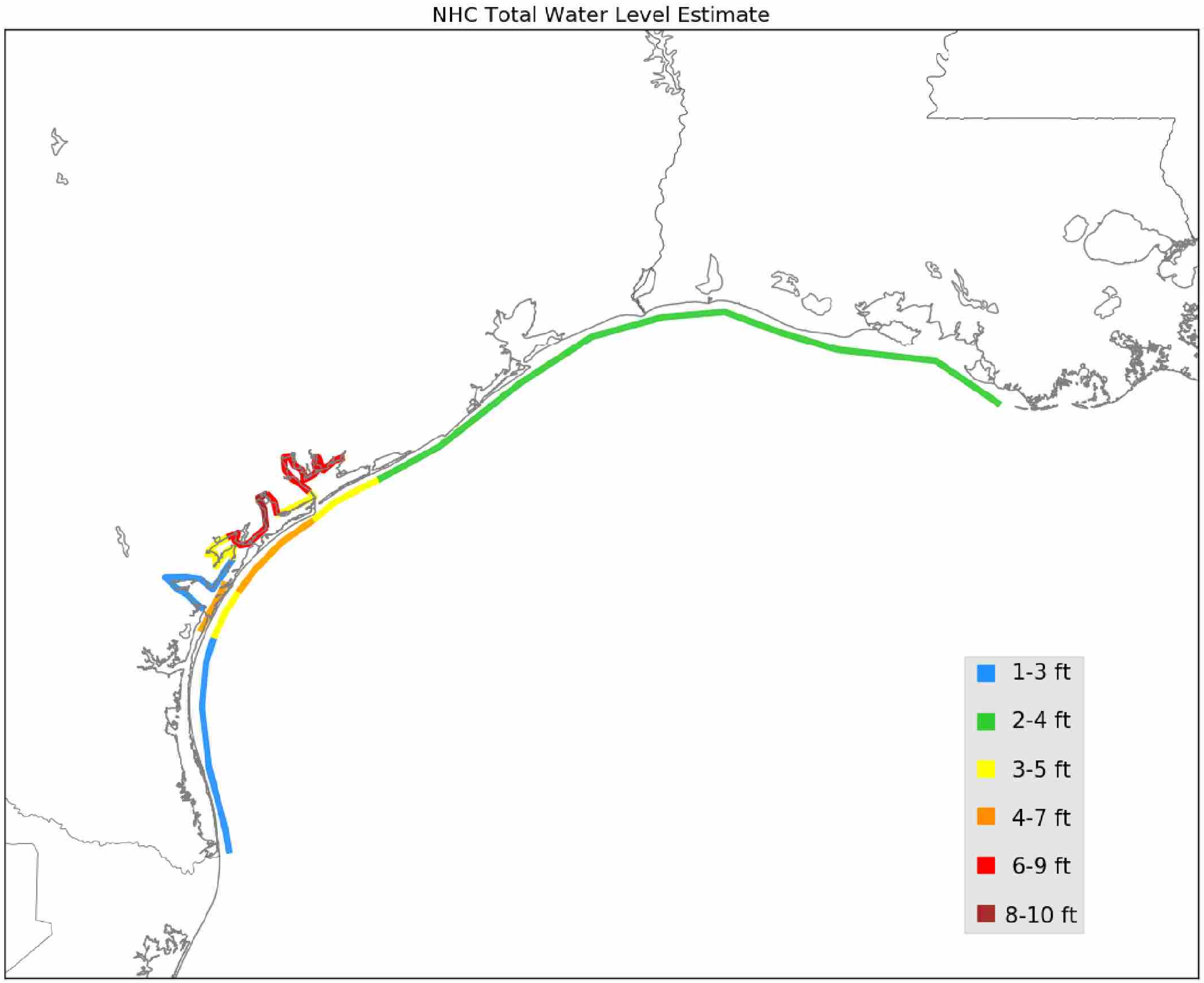


Figure 5. Analyzed storm surge inundation (feet above ground level) along the coast of Texas and Louisiana from Hurricane Harvey. Image courtesy NHC Storm Surge Unit.

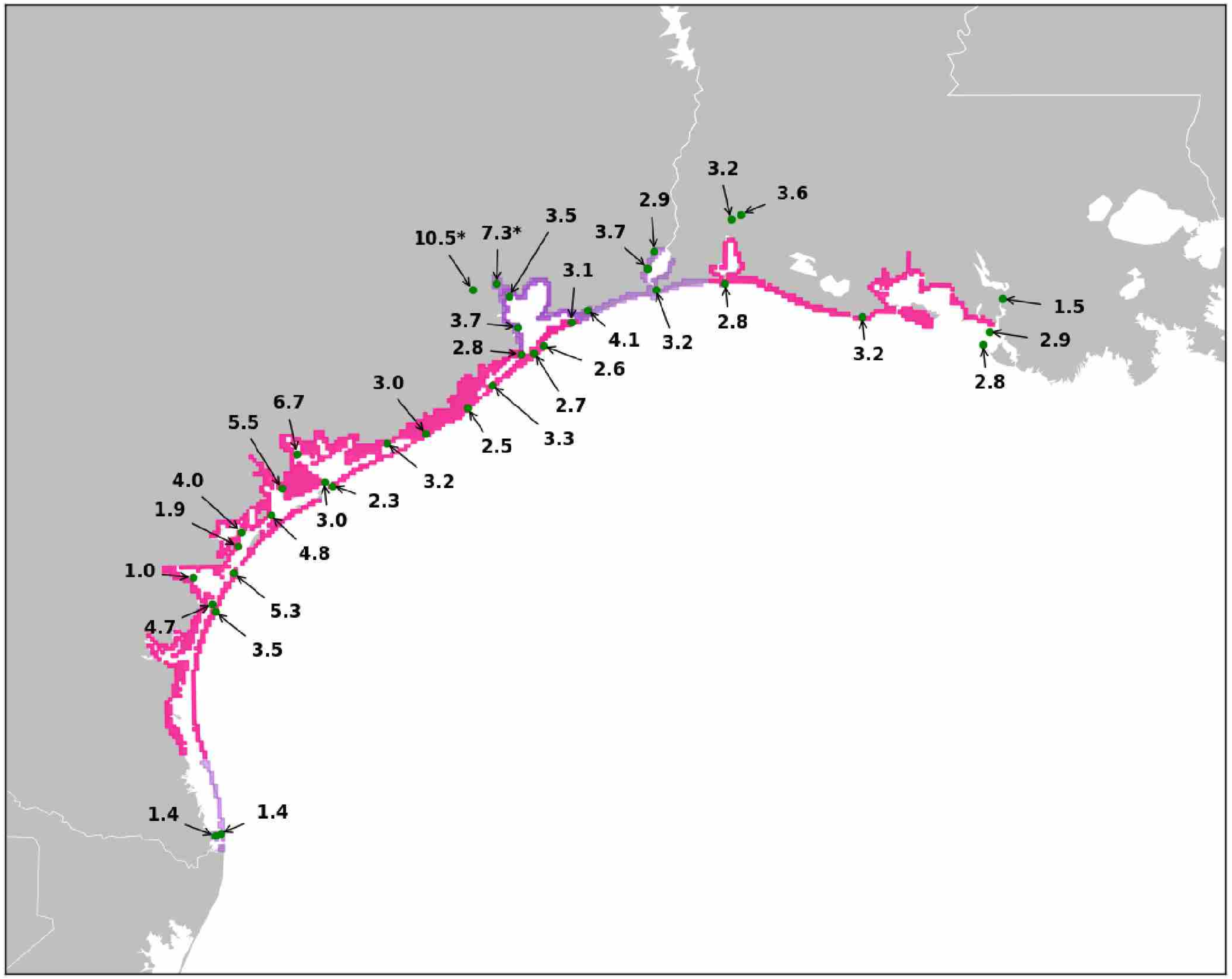


Figure 6. Maximum water levels (feet) measured from tide gauges along the coasts of Texas and Louisiana during Hurricane Harvey and areas covered by storm surge warnings (magenta) and watches (lavender). Water levels are referenced above Mean Higher High Water (MHHW), which is used as a proxy for inundation (above ground level) on normally dry ground along the immediate coastline. Image courtesy of the NHC Storm Surge Unit. Note starred values are contaminated by excessive flood runoff.

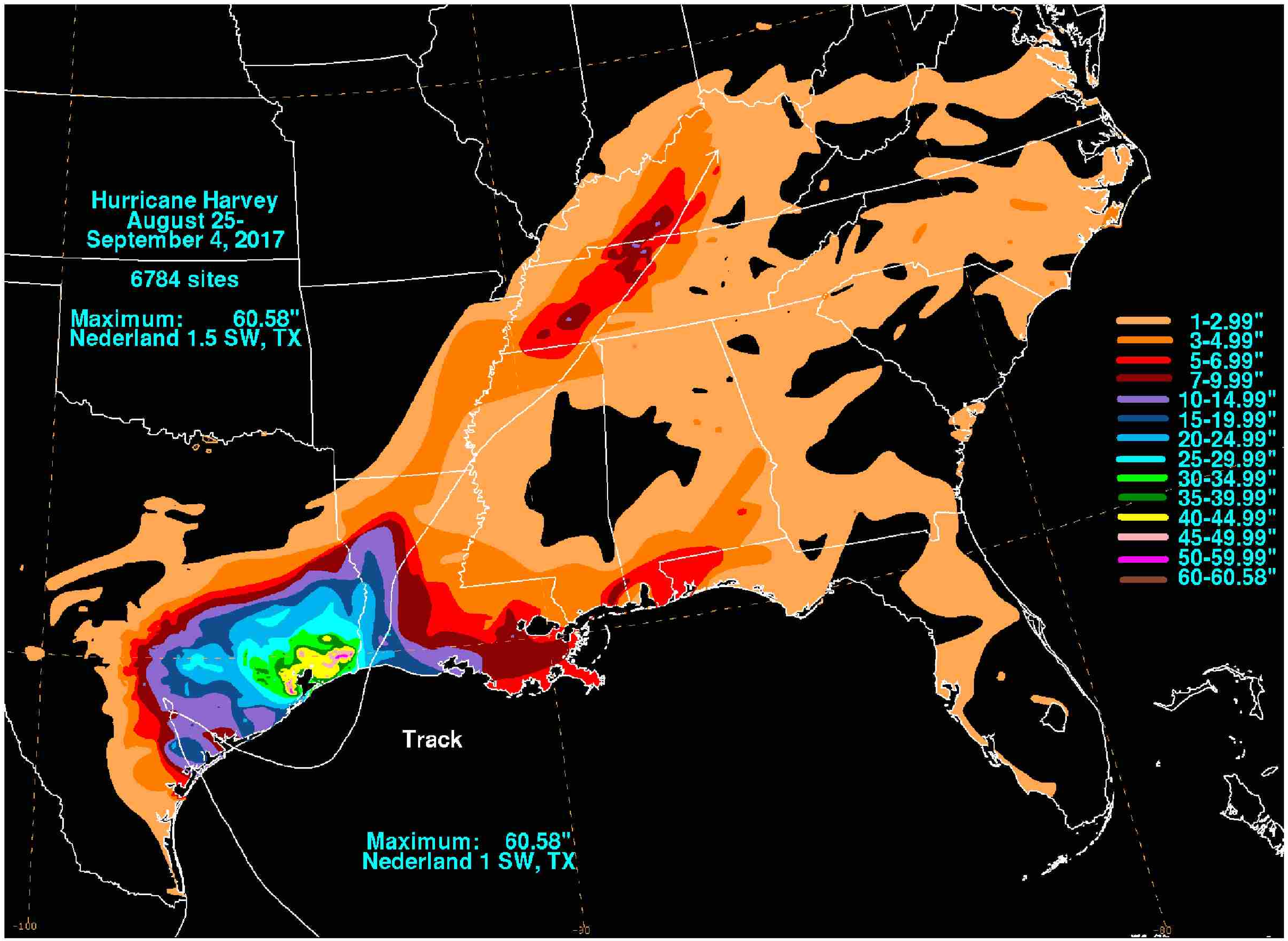


Figure 7. Observed rainfall totals (inches) in association with Harvey and its remnants. Figure courtesy David Roth (WPC).

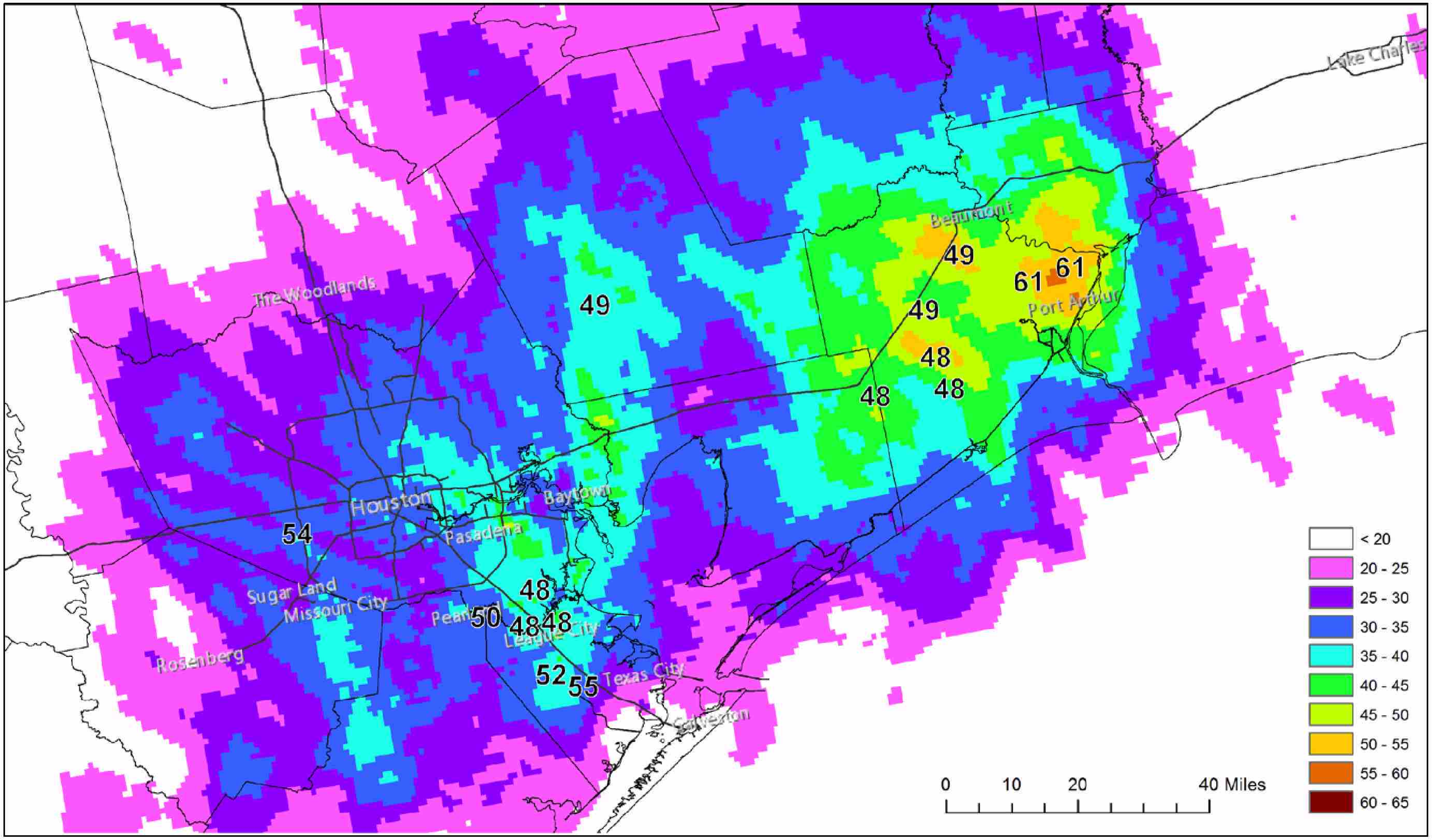


Figure 8. NOAA gauge-corrected, multi-radar multi-sensor quantitative precipitation estimates for Harvey (inches), 25 August-1 September 2017. The black numbers are actual rain gauge values, all of which exceed the previous U.S. continental rainfall record for a tropical cyclone.

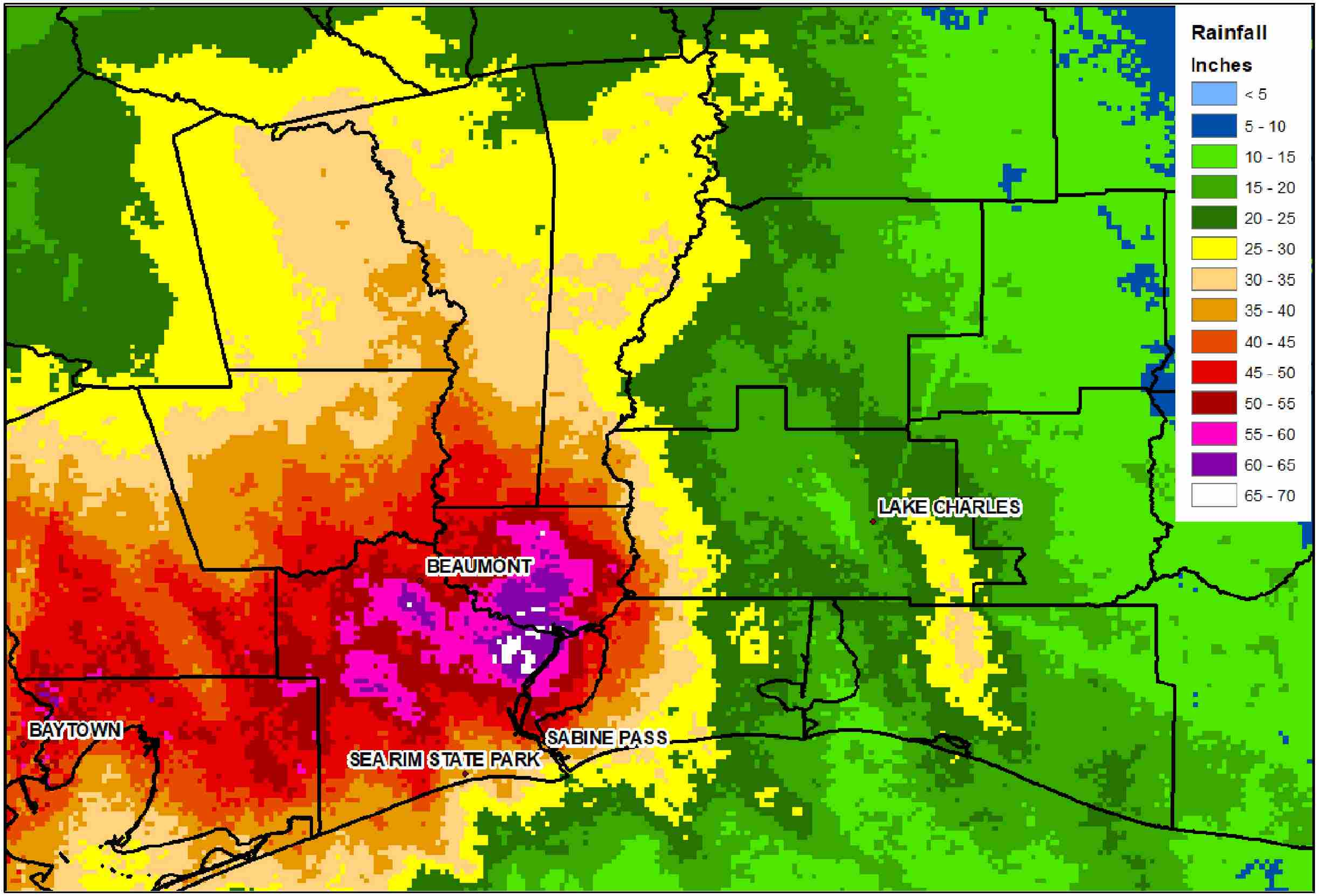


Figure 9. Raw NOAA Multi-radar multi-sensor quantitative precipitation estimation (inches) for Harvey in southeastern Texas from 25 August to 1 September 2017. Figure courtesy Jonathan Brazzell of NWS Lake Charles.

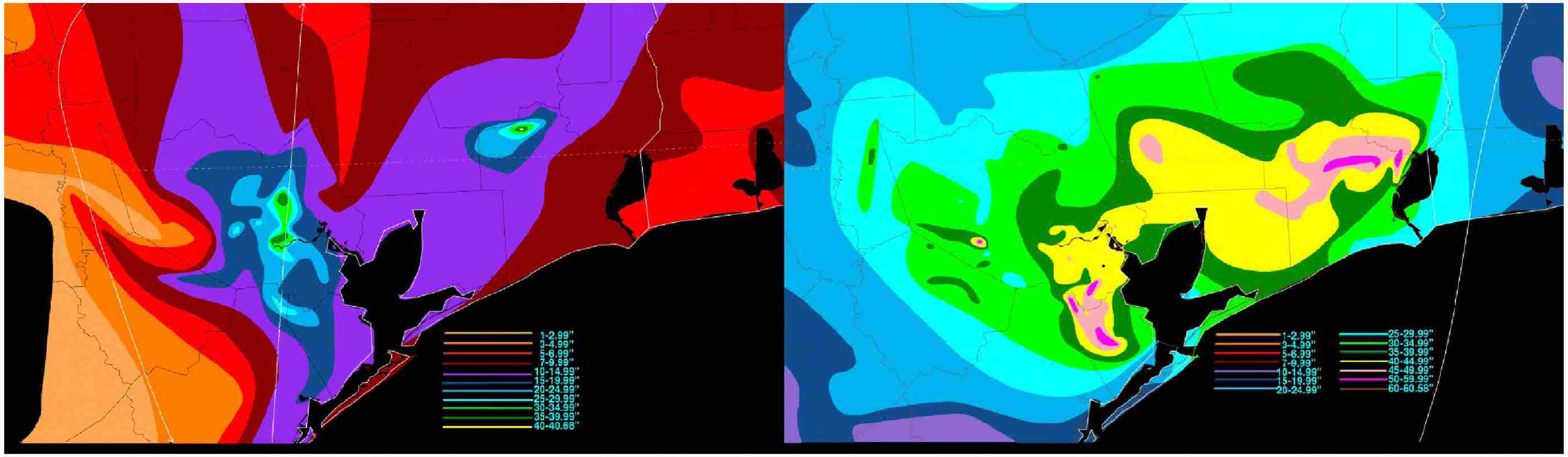


Figure 10a. Allison (2001) rainfall totals (left) vs Harvey rainfall totals (right) in inches for southeastern Texas with the same color and map scale. Note almost every location in SE Texas had considerably more rainfall during Harvey. Figure courtesy David Roth (WPC).

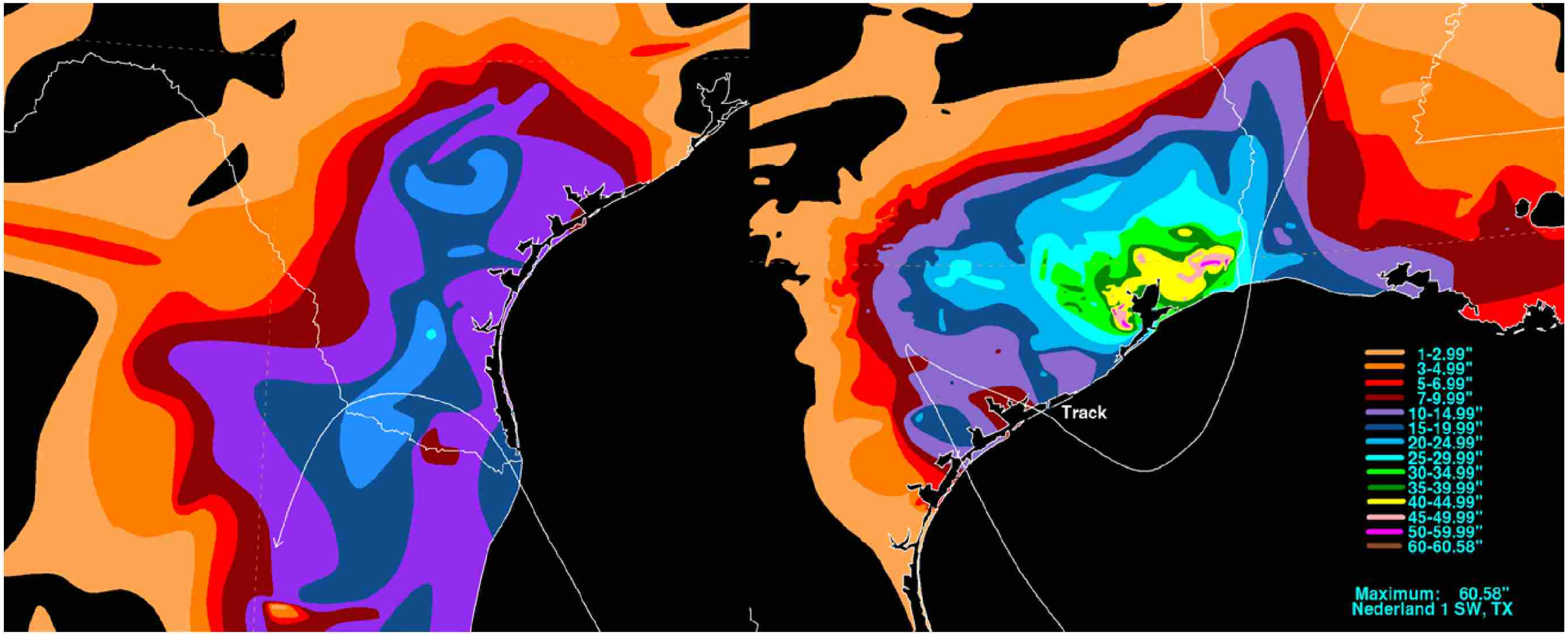


Figure 10b. As in Figure 10a except for Beulah (1967) rainfall (left).

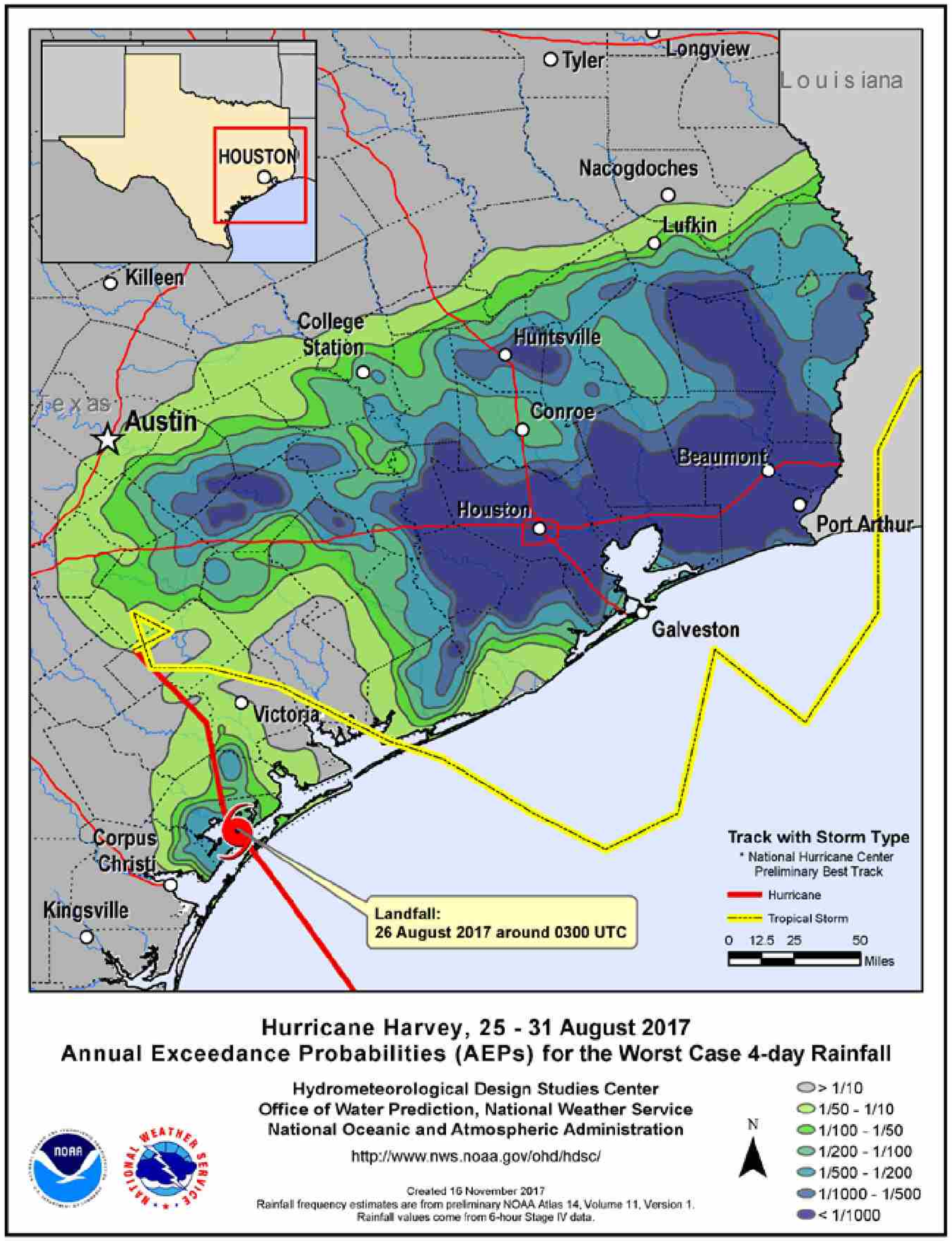


Figure 11. Annual 4-day rainfall exceedance probabilities for Harvey. Image courtesy NOAA Office of Water Prediction. Note that the track shown on the graphic was preliminary and does not reflect the final NHC best track.

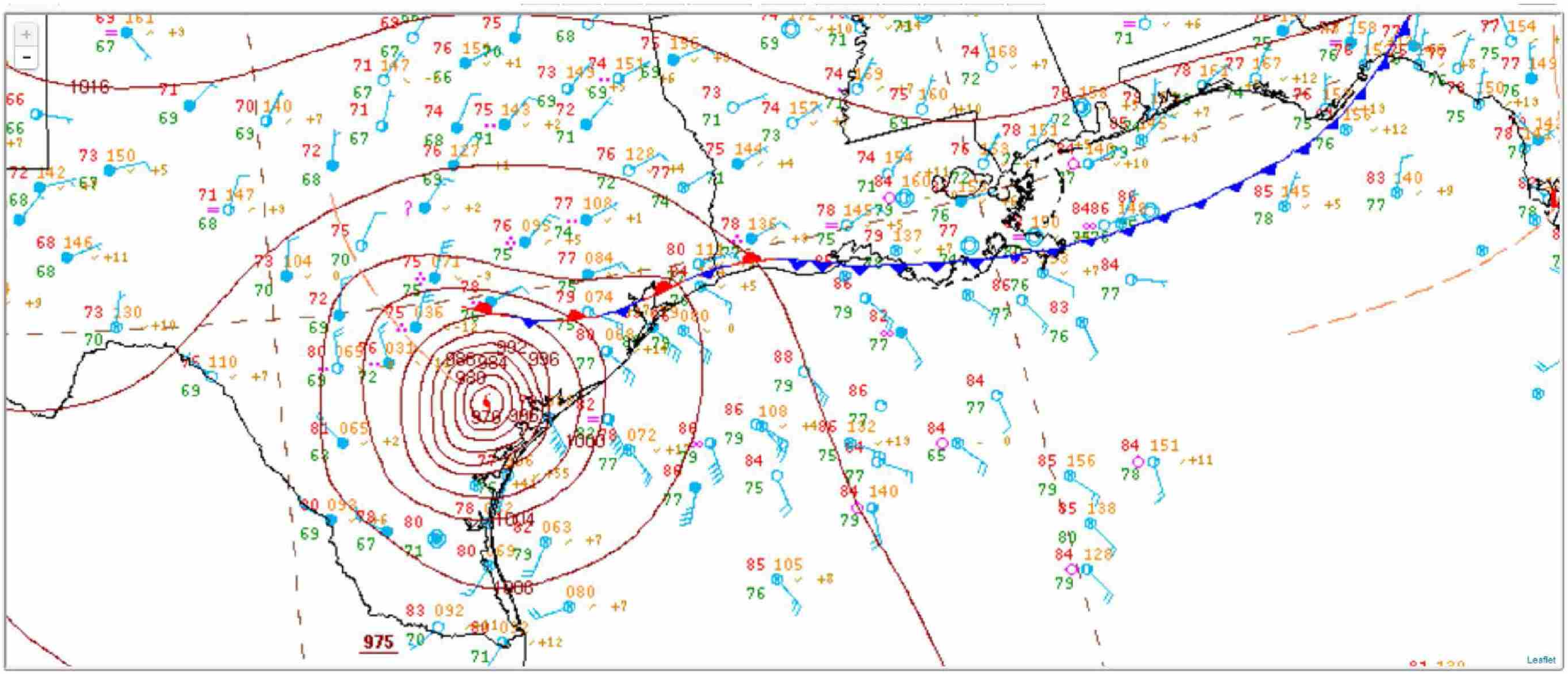

Figure 12. NCEP unified surface analysis at 1200 UTC 26 August 2017.

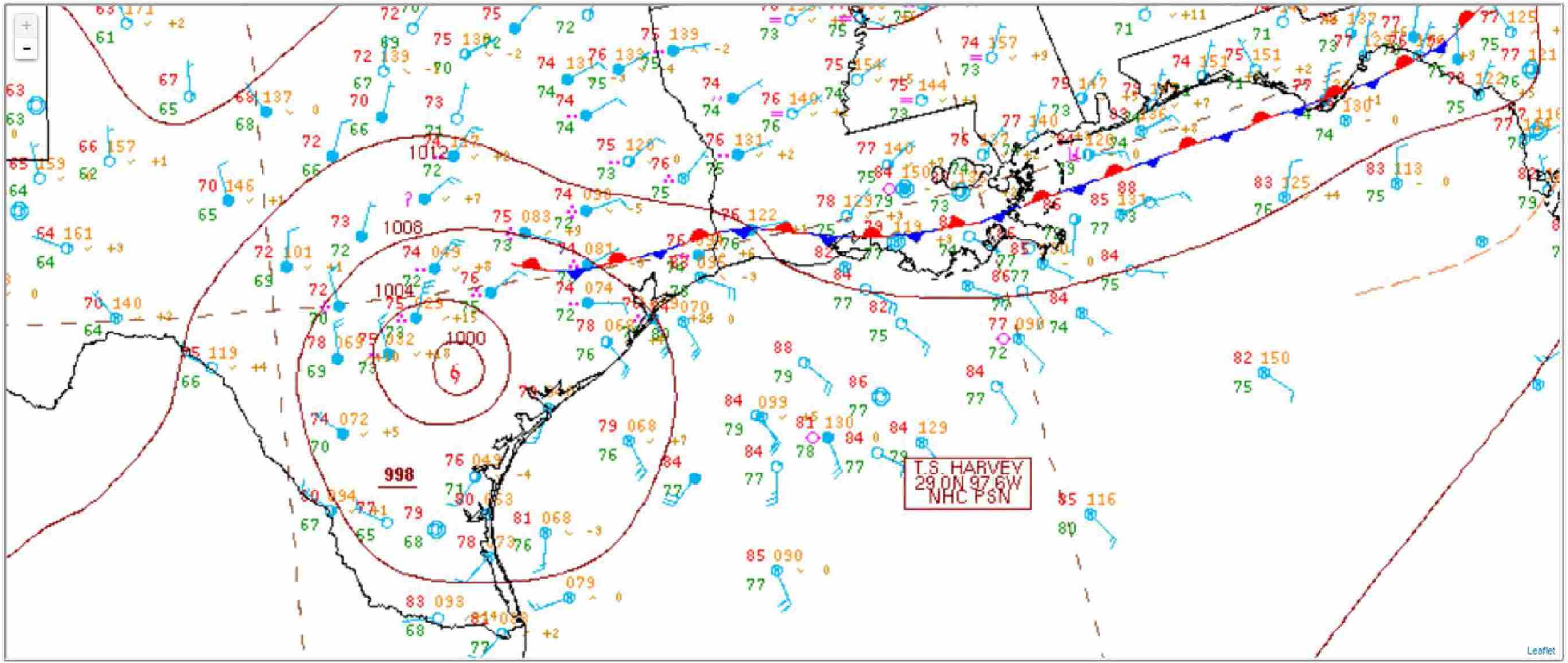


Figure 13. NCEP unified surface analysis at 1200 UTC 27 August 2017.

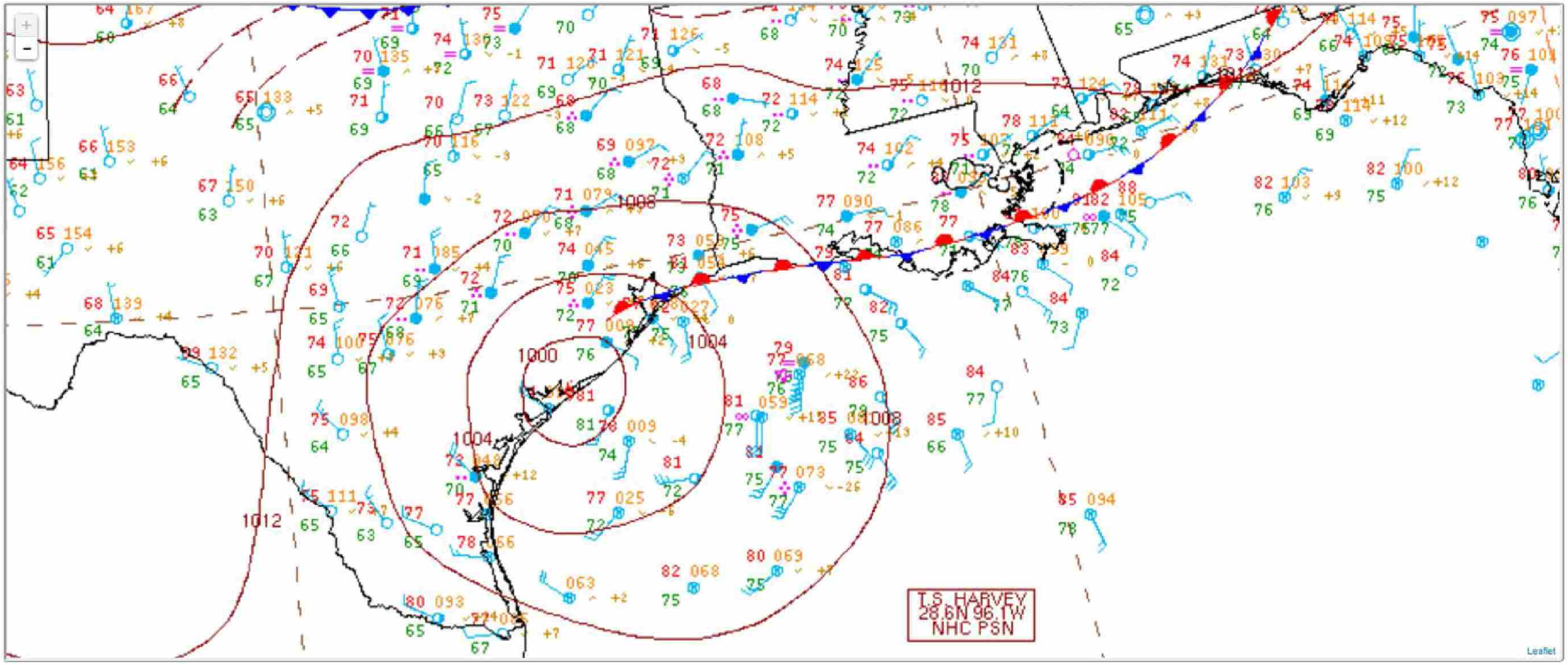


Figure 14. NCEP unified surface analysis at 1200 UTC 28 August 2017.

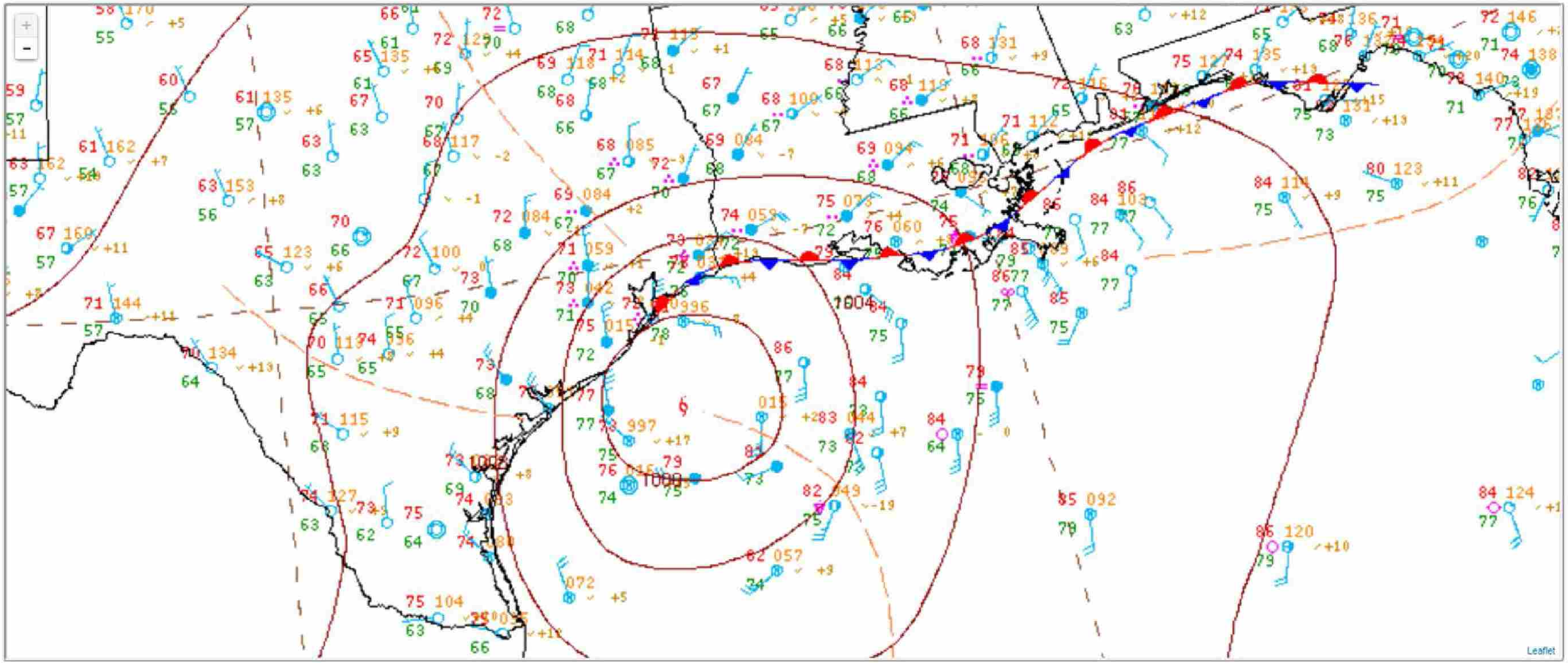


Figure 15. NCEP unified surface analysis at 1200 UTC 29 August 2017.

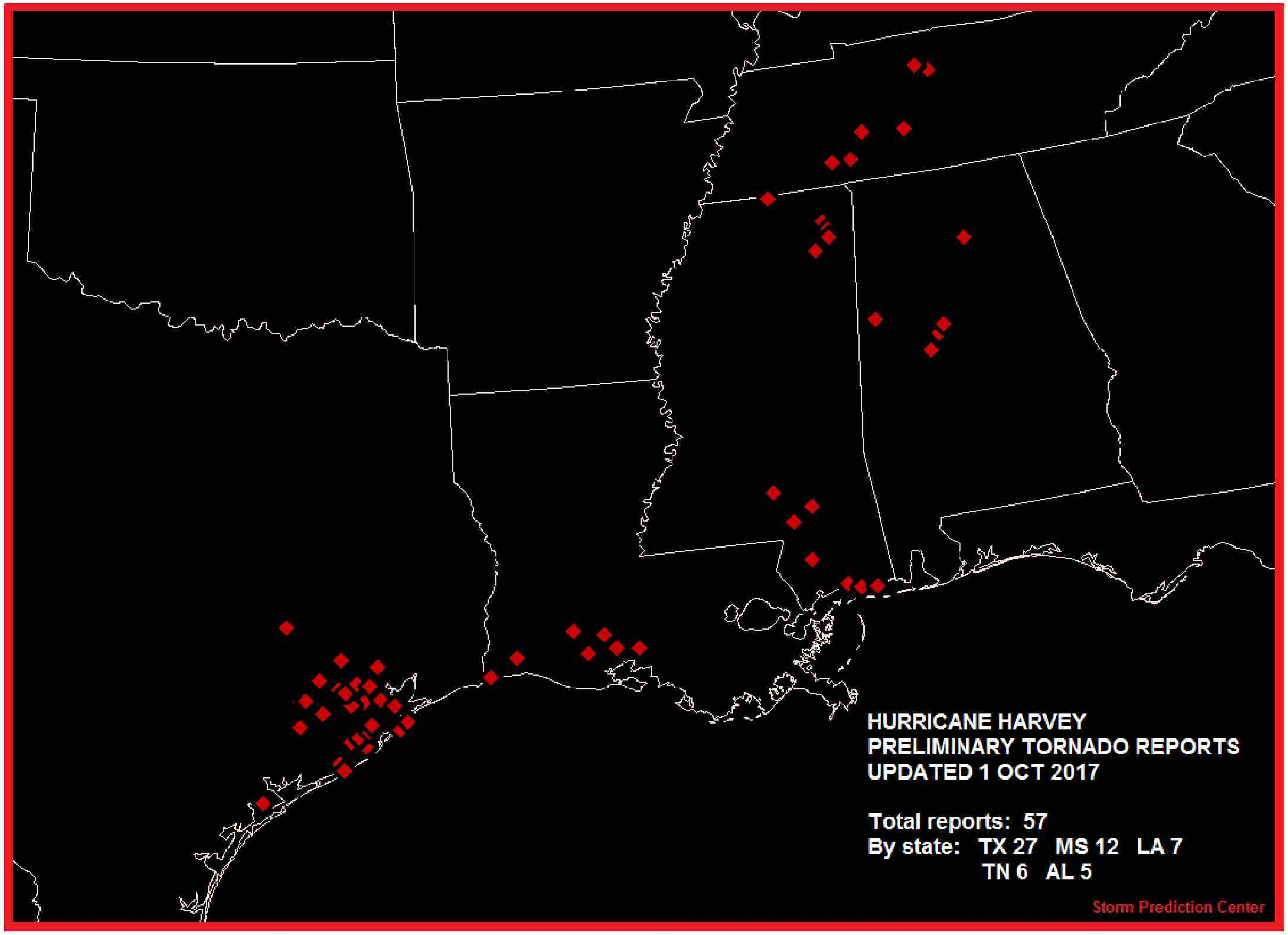


Figure 16. Preliminary tornado reports from Harvey. Figure courtesy of the Storm Prediction Center.

Figure 17. Texas World Speedway after Harvey being used to store flooded cars. Photo credit Brazos Drones.


Figure 18. An example of the water rescues that were ongoing during Harvey in Houston on 27 August 2017. Photo credit David J. Phillip (Associated Press).

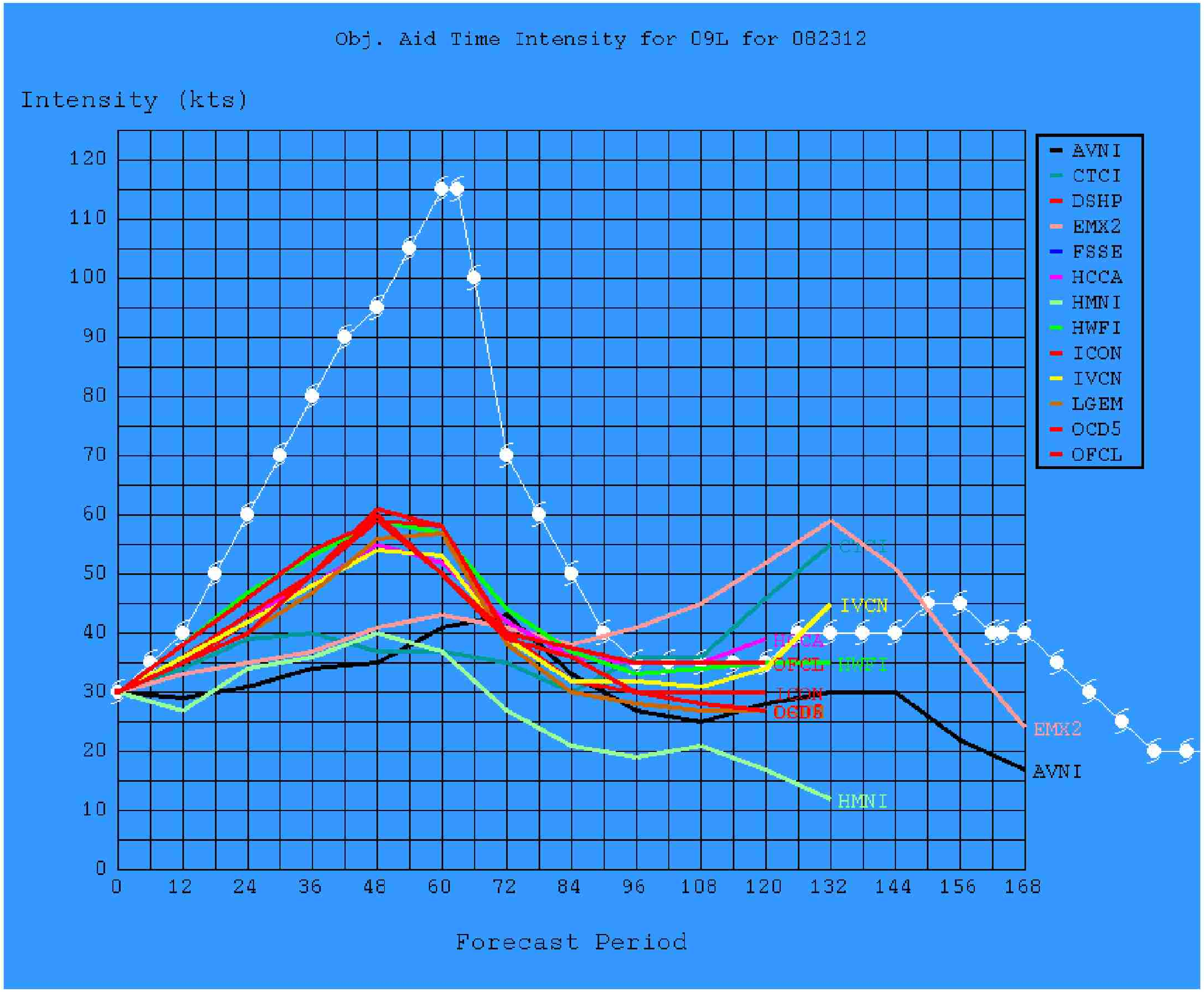


Figure 19. NHC intensity aids (knots, colored lines) for the 1200 UTC 23 August 2017 forecast cycle for Harvey (verifying points in white). Note the guidance was much too low for the intensity at landfall, which occurred near the 60 h point.

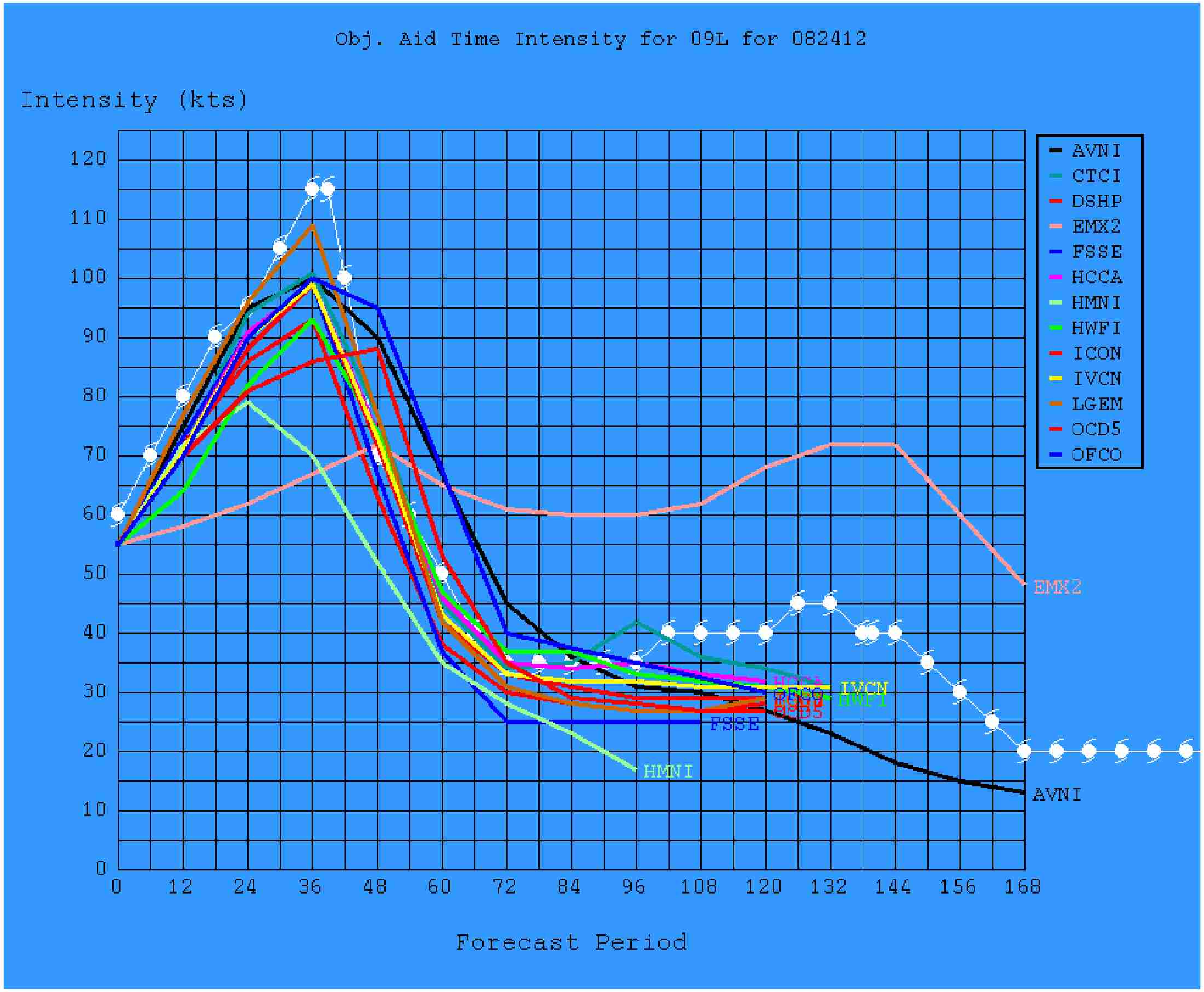


Figure 20. Same as Figure 14 but for 1200 UTC 24 August 2017. Note that much of the guidance showed rapid intensification before landfall, which occurred near the 36 h forecast point.

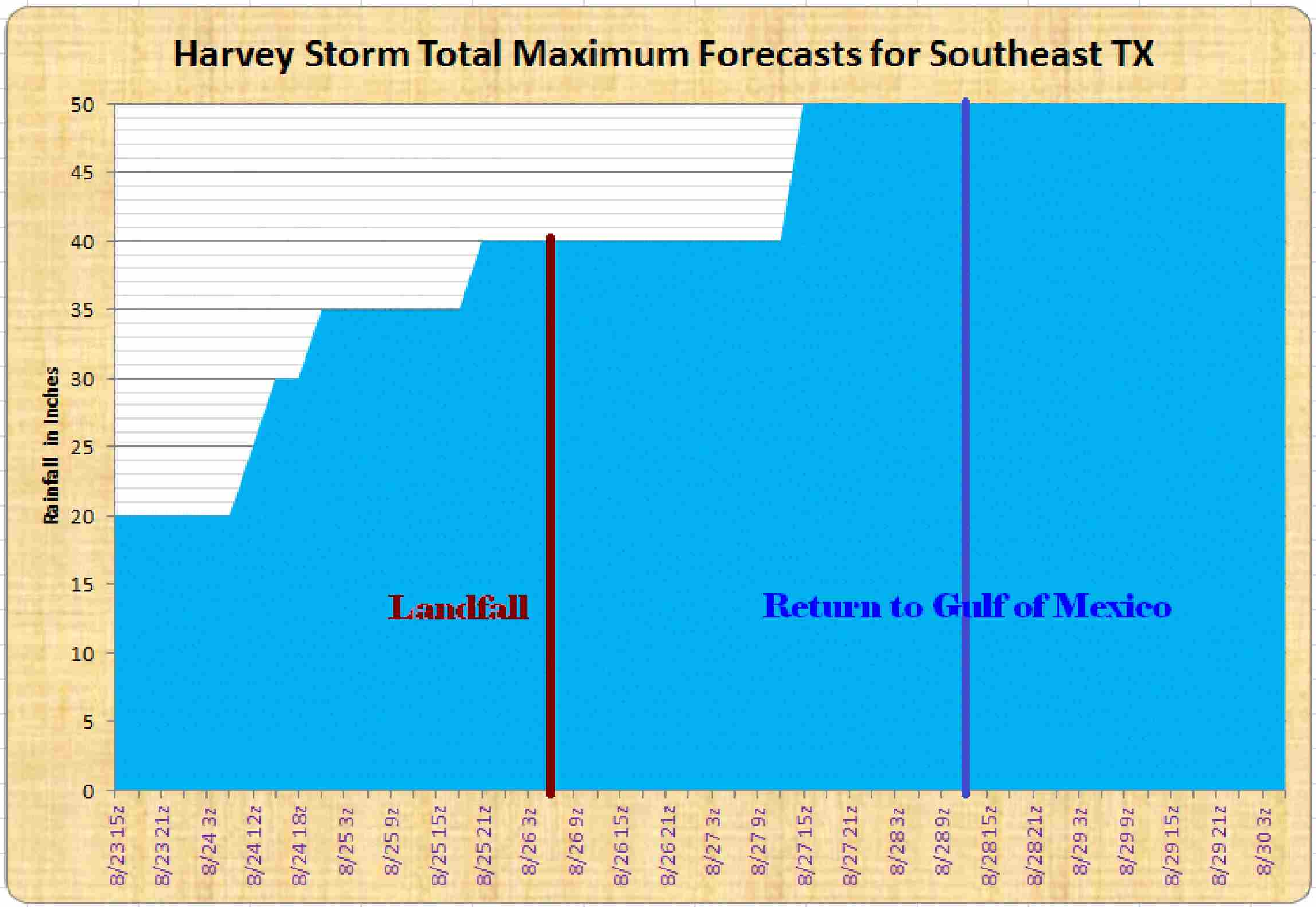


Figure 21. Time series of maximum rainfall forecasts for Harvey in southeastern Texas. Figure courtesy David Roth (WPC)

US Army Corps of Engineers
BUILDING STRONG®

# Corps releases at Addicks and Barker Dams to begin

*Posted 8/28/2017*

Release no. 17-031

**Contact**
Randy Cephus
swgpao@usace.army.mil

GALVESTON, Texas–The U.S. Army Corps of Engineers Galveston District is starting water releases immediately from Addicks and Barker dams because water levels in the reservoirs have increased dramatically in the last few hours.

“Residents adjacent to the reservoirs need to be vigilant because the water in the reservoirs is rising rapidly,” said Col. Lars Zetterstrom, Galveston District commander. “Both reservoirs are rising more than half a foot per hour.”

According to Corps models, at this rate the first home in Addicks Reservoir will be impacted in 2 to 4 hours and the first home in Barker Reservoir will be impacted later this morning.

The Corps will start releasing around 800 cubic feet per second from each reservoir for a total of 1,600 c.f.s. Within the next 6 to 10 hours we will be releasing 4,000 c.f.s. from both reservoirs, for a combined total of 8,000 c.f.s.

“If we don’t begin releasing now, the volume of uncontrolled water around the dams will be higher and have a greater impact on the surrounding communities,” said Zetterstrom. “We are coordinating floodwater releases from Addicks and Barker with the Harris County Flood Control District so they can make informed decisions for the communities they support.”

Zetterstrom noted that the water in the reservoirs will flow into the Buffalo Bayou whether it goes through the gates or around the end of the dams.

“It’s going to be better to release the water through the gates directly into Buffalo Bayou as opposed to letting it go around the end and through additional neighborhoods and ultimately into the bayou,” Zetterstrom said.

The Corps is confident that the structures continue to perform as they were designed to do.

“This flood event will exceed the 2016 tax day flood elevations,” Zetterstrom said. “During the 2016 tax day flood Addicks and Barker Dams reduced Buffalo Bayou’s peak discharge from 132,853 c.f.s. to 7,160 c.f.s.”

“Public safety continues to be our number one concern as we work closely with our partners - the City of Houston, Fort Bend County, Harris County and the Texas Dept. of Public Safety - to monitor the reservoirs,” said Zetterstrom. “Residents should always listen to and follow instructions of local emergency management officials.”

Learn more about the Texas coast at http://www.swg.usace.army.mil/Missions/TexasCoastValuetotheNation.aspx. For news and information, visit www.swg.usace.army.mil. Find us on Facebook, www.facebook.com/GalvestonDistrict or follow us on Twitter, www.twitter.com/USACEgalveston.

2

5TH CONGRESS } HOUSE OF REPRESENTATIVES { DOCUMENT
2d Session } { No. 456

# OUSTON SHIP CHANNEL AND BUFFALO BAYOU, TEX.

LETTER

FROM

# THE SECRETARY OF WAR

TRANSMITTING

LETTER FROM THE CHIEF OF ENGINEERS, UNITED STATES ARMY, DATED NOVEMBER 26, 1937, SUBMITTING A REPORT, TOGETHER WITH ACCOMPANYING PAPERS AND ILLUSTRATIONS, ON A REEXAMINATION OF HOUSTON SHIP CHANNEL, TEX., SUBMITTED IN RIVERS AND HARBORS COMMITTEE DOCUMENT NO. 58, SEVENTY-FOURTH CONGRESS, FIRST SESSION, AND PRELIMINARY EXAMINATION AND SURVEY OF BUFFALO BAYOU, TEX., REQUESTED BY RESOLUTION OF THE COMMITTEE ON COMMERCE OF THE UNITED STATES SENATE, APPROVED FEBRUARY 20, 1936, AND THE FLOOD CONTROL ACT APPROVED JUNE 22, 1936

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DECEMBER 17, 1937.—Referred to the Committee on Rivers and Harbors and ordered to be printed, with 6 illustrations

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WAR DEPARTMENT,
*Washington, December 11, 1937.*

The SPEAKER OF THE HOUSE OF REPRESENTATIVES.

DEAR MR. SPEAKER: I am transmitting herewith a report dated November 26, 1937, from the Chief of Engineers, United States Army, on preliminary examination and survey of, and review of reports on Houston Ship Channel and Buffalo Bayou, Tex., submitted in Committee on Rivers and Harbors Document 58, Seventy-fourth Congress, first session, United States House of Representatives, and requested by resolution of the Committee on Commerce of the United States Senate approved February 20, 1936, and the Flood Control Act approved June 22, 1936, together with accompanying papers and illustrations.

Sincerely yours,

HARRY H. WOODRING,
*Secretary of War.*

34177—38——1

Scanned for
Galveston Intranet

WAR DEPARTMENT,
OFFICE OF THE CHIEF OF ENGINEERS,
*Washington, November 26, 1937*

Subject: Preliminary examination and survey of Houston S
Channel and Buffalo Bayou, Tex.
To: The Secretary of War.

1. I submit, for transmission to Congress, my report with acco panying papers and illustrations on preliminary examination and s vey for flood control of Buffalo Bayou, Tex., authorized by Flood Control Act approved June 22, 1936. Included is the rep of the Board of Engineers for Rivers and Harbors in response to resolution adopted February 20, 1936, by the Committee on Co merce of the United States Senate, requesting the Board to revi the report on the Houston Ship Channel, Tex., submitted in Co mittee on Rivers and Harbors Committee Document No. 58, Sevent fourth Congress, first session, and previous reports, with a view to t improvement of said channels and their protection from the depo of silt, consideration being given to the question of cooperation on t part of local interests.

2. Buffalo Bayou rises in the gently sloping coastal prairie of sout eastern Texas, flows generally eastward in a narrow and tortuo channel 75 miles long, passing through the city of Houston, an enters the San Jacinto River 9 miles above Galveston Bay. It drai a watershed of 1,024 square miles, including 70 square miles lyin within the corporate limits of the city. The lower reaches of th bayou have been improved as part of the Houston Ship Channe which affords deep-draft ocean navigation to extensive termin developments in and below Houston. The authorized project for im provement of the ship channel provides for a depth of 34 feet, wit appropriate widths, from deep water in Galveston Bay to and in th Houston turning basin. The project provides also for a light-draf channel for the accommodation of barge traffic in Buffalo Bayou to the mouth of White Oak Bayou at Main Street, 6½ miles above the turning basin. The total cost for new work of improvement to June 30, 1936, was $11,906,026.66, exclusive of contributed funds totaling $2,574,178.78. The estimated annual cost of maintenance is $800,000.

3. Floods in the Buffalo Bayou Watershed result from the rapi run-off of heavy precipitation during cyclonic disturbances of tropica or extratropical origin. Extensive areas both in and above the cit of Houston are inundated. Damages occur chiefly in the wholesal commercial district of the city above Main Street, where the encroach ment of buildings, bridges, and other structures on the natural floo channel causes appreciably increased flood heights. Of the six majo floods of record since 1854, reliable data as to stream discharge an flood damages are available only for those of May 1929 and Decem ber 1935. The former, with an indicated peak discharge totaling 30,500 cubic feet per second from the combined watersheds of Buffal and White Oak Bayous above Main Street, caused property damage within the city reported by the Houston Chamber of Commerce a $1,392,442.76. The flood of 1935, with a peak discharge of 53,00 cubic feet per second, just below Main Street, inundated some 2 blocks in the business and 100 blocks in the residential sections causing the loss of eight lives and property losses reported at $2,528,

)6.31, and seriously interrupting both rail and highway traffic. Ex-nsive areas of farm and pasture lands above the city were inundated, ıt without appreciable damage. Navigation in the ship channel as interrupted for a period of 3 days because of high current veloc-les; and further delays were caused by excessive shoaling of the rning basin, due chiefly to the deposit of materials eroded from the ;ht-draft channel above. The flood of 1935 resulted from a 3-day infall averaging 15 inches on the watershed of Buffalo Bayou above ain Street and 12.7 inches in the White Oak Basin. Existing rain-ll records for the entire State of Texas indicate the possibility of a aximum average 3-day storm precipitation of over 30 inches for the ea in question, with probable maximum crest discharges totaling arly 90,000 cubic feet per second from the Buffalo Bayou Water-ed above Main Street, about half that amount from the White Oak asin, and 105,000 cubic feet per second below the junction of the ro streams.

4. No project for the control of floods in Buffalo Bayou or the pre-ntion of the resultant silt deposits in the Houston Ship Channel s been authorized by Congress. The city of Houston has expended proximately $1,000,000 in the construction of a concrete-lined annel 1,300 feet long in Buffalo Bayou ½ mile above Main Street, th but limited benefit due to the restricted capacity of the channel low. Additional sums have been expended in the enlargement and ctification of the channels of two tributaries entering Buffalo Bayou low the turning basin. The improvement now generally desired local interests is the prosecution of measures for the control floods in Buffalo and White Oak Bayous above their junction to clude the prevention of undue shoaling in the navigation provement.

5. The reporting officers have considered various plans for the ntrol of floods on Buffalo and White Oak Bayous, including regu-tion by storage, diversion, channel rectification and enlargement excavation or by levees, and combinations thereof. The most itable improvement, as proposed by the division engineer, contem-ıtes the construction of a detention reservoir of 265,000-acre-foot pacity on Buffalo Bayou some 27 river miles above Main Street; largement of the Buffalo Bayou Channel between the western city ıits and Main Street to carry the maximum probable regulated w in this section; improvement of White Oak Bayou within the y limits to provide adequate flood openings through bridges, levees ere necessary to prevent overflow into Buffalo Bayou above Main eet, and the establishment of building lines and the prevention of mping; improvement of the Buffalo Bayou channel between Main eet and the turning basin to provide a discharge capacity of 70,000 bic feet per second; and the construction of velocity-control works the channel just above the turning basin. This improvement, signated "plan IV," is estimated to cost $9,000,000 for construction ms of the type normally provided at Federal expense and excluding penditures incidental to the reconstruction or removal of existing uctures and the acquisition of rights-of-way and flowage easements. ıch of the latter-type work included in the plan represents addi-ns and betterments to existing streets, bridges, sewage, and other ilities, or modifications to structures now encroaching upon the eam channel; and should be accomplished in the near future regard-

less of the adoption of a flood-control plan. Excluding the cos such items as being justified by resultant increased property val the division engineer arrives at a net total cost for right-of-way it of $3,075,500. The annual benefits of the improvement through prevention of flood damages and interruptions to business and ductions in maintenance dredging costs are estimated to ave $730,000. This sum capitalized at 6 percent would justify an in expenditure of $12,167,000; to which are added $100,000 for bet ments to the light-draft channel above the turning basin and $5,000 for the enhancement of property values, bringing the total capital benefits to $17,267,000. This sum substantially exceeds the net of the improvement proposed.

6. The Board of Engineers for Rivers and Harbors notes that gradual encroachment of bridges, buildings, and other structures the natural flood channel of Buffalo Bayou within the city of Hous has created a serious flood problem. The flood of December 1 resulted in the loss of eight lives and property damage of sev millions of dollars. Investigations by the district engineer disc the likelihood of substantially greater floods in the future, with d ages far in excess of any heretofore suffered. Navigation is ha capped during severe floods by extensive shoaling and high veloci in the upper reaches of the ship channel; and the already high costs for maintenance dredging may be expected further to incr as the areas available for the deposit of dredged materials are hausted. The Board concurs with the reporting officers in the v that a substantial expenditure is justified for the alleviation of flood problems of the city and port of Houston. Plan IV, as rec mended by the division engineer, appears to offer the most effec solution for the combined problems of flood control and naviga at the locality. The details of a cooperative undertaking of magnitude, many features of which must be coordinated with mun pal or local plans not yet fully developed, should be left to the fu determination of the Department. The Board accordingly rec mends the prosecution of works for the control of floods in Bu Bayou and the prevention of shoaling in the turning basin of Houston Ship Channel, at an estimated Federal cost not to ex $9,000,000 specifically limited to the defraying of cost of construc of channels and structures designed for flood-control and silt- vention purposes, subject to certain measures of local cooperatio

7. After due consideration of these reports, I concur in the vi and recommendations of the Board. The loss of life, heavy prop damage, and disruption to the commerce of the city and po f Houston occasioned by the flood of 1935 have demonstrated the ur t need for the prosecution of comprehensive and effective measure r the control of future floods in Buffalo Bayou. The general progra f improvement contemplated by plan IV appears to be fully justifie y the resultant benefits to the locality and to navigation. The prop d division of costs between the Federal Government and local inte s is in conformity with the policies established by Congress in the F d Control Act approved June 22, 1936. I, therefore, recommend e improvement of Buffalo Bayou and its tributaries above the tu g basin of the Houston Ship Channel to provide for the control of flo s, the protection of the city of Houston from flood damages, and e prevention of the deposit of silt in the turning basin of the Hou n

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Ship Channel, by means of detention reservoirs, enlargement and rectification of channels, the construction of control works, and any diversions which may be found advisable, at an estimated Federal cost not to exceed $9,000,000, specifically limited to the defraying of costs of construction of channels and structures designed for flood-control and silt-prevention purposes and excluding (a) the cost of all rights-of-way and flowage easements; (b) the costs incidental to the reconstruction, relocation, or modification of existing structures, bridges, buildings, railways, highways, utilities, and public and private facilities and properties of all kinds, except such as are integral parts of flood-control structures; and (c) the cost of that portion of flood-control channels or structures which is designed and constructed for other than flood-control purposes: *Provided*, That a single local agency be formed and vested with authority to act for, and in the name of, all interested parties, other than the Federal Government, in all matters pertaining to the formation, planning, financing, construction, and maintenance of the proposed project: *Provided further*, That the local agency aforesaid shall (a) provide without cost to the United States all lands, easements, and rights-of-way necessary for the construction of the project; (b) hold and save the United States free from damages due to the construction of such works; (c) maintain and operate all of the works after completion in accordance with regulations prescribed by the Secretary of War: *Provided further*, That the local agency will take such measures as may be necessary to (a) establish and enforce building lines approved by the Secretary of War for the protection of the floodway areas against further encroachments; (b) prevent further dumping of waste materials upon existing banks of streams or within said building lines; (c) give assurances satisfactory to the Secretary of War that the existing obstructions to, and encroachments upon, the stream channels within the city of Houston will be removed by and at the sole expense of the owner or local agency as the initial step in the development of the adopted flood-control plan: And *provided further*, That the Secretary of War shall have final decision as to (a) the type and adequacy of plans for all works which function in whole or in part to serve flood-control purposes; (b) the portion of the cost of such works, designed and constructed so as to serve other than flood-control purposes, which is properly chargeable to the flood-control feature of the project.

J. L. Schley, *Major General,*
*Chief of Engineers.*

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## REPORT OF THE BOARD OF ENGINEERS FOR RIVERS AND HARBORS

War Department,
Board of Engineers for Rivers and Harbors,
*Washington, July 19, 1937.*

Subject: Houston Ship Channel, Texas.
To: The Chief of Engineers, United States Army.

1. This report is in response to the following resolution, adopted February 20, 1936:

*Resolved by the Committee on Commerce of the United States Senate*, That the Board of Engineers for Rivers and Harbors, created under section 3 of the River and Harbor Act, approved June 13, 1902, is hereby requested to review the report

on the Houston Ship Channel, Texas, submitted in Committee on Rivers and Harbors Document No. 58, Seventy-fourth Congress, first session, and previous reports, with a view to the improvement of said channels and their protection from the deposit of silt, consideration being given to the question of cooperation on the part of local interests.

Included is a review of the reports on preliminary examination and survey for flood control of "Buffalo Bayou, Texas," authorized by the Flood Control Act approved June 22, 1936.

2. Buffalo Bayou has its source in the gently sloping prairie bordering the coast of Texas, flows generally eastward 75 miles in a narrow and tortuous channel, and enters the San Jacinto River 9 miles above the mouth of the latter at the head of Galveston Bay. The city of Houston occupies an area of 70 square miles on both sides of the stream, its upper and lower limits being 31 and 12 miles, respectively, above the mouth. The Houston Ship Channel extends from deep water at the entrance to Galveston Bay northward 25 miles across the open shallow waters of the bay to Morgan Point, thence northwest and west an additional 25 miles up San Jacinto Bay and River and Buffalo Bayou to a turning basin in the city of Houston; whence a light-draft channel continues up the bayou an additional distance of 6½ miles to the mouth of White Oak Bayou at Main Street. The present project for its improvement provides for a depth of 34 feet from deep water in Galveston Bay to and including the Houston turning basin, with general widths of 400 feet through the bay, thence 300, 250, and 200 feet to the turning basin; a depth of 10 feet and width of 60 feet in the light-draft channel above the turning basin; and for the construction of a dike some 5 miles in length to protect the channel in upper Galveston Bay. The work of deepening the channel from 32 to 34 feet, authorized by the River and Harbor Act approved August 30, 1935, is now under way. The total cost of the improvement to June 30, 1936, was $11,906,026.66 for new work and $7,707,489.76 for maintenance, exclusive of contributed funds totaling $2,774,187.78. The estimated annual cost of maintenance is $800,000. The city of Houston expended $45,000 in the initial dredging of the light-draft channel above the turning basin to a depth of 8 feet and width of 40 feet; and the city, the Houston Ship Channel Navigation District, and private interests have constructed extensive terminal facilities along the upper reaches of the deep-draft channel. The mean range of tide decreases from 1.3 feet in lower Galveston Bay to less than 0.5 foot in San Jacinto River and Buffalo Bayou.

3. Major floods in Buffalo Bayou result from heavy precipitation during tropical hurricanes moving in from the Gulf or similar disturbances traveling eastward across the continent. Its drainage basin, roughly 50 miles long and up to 30 miles in width, rises gently toward the northwest at a rate less than 3 feet per mile. The water courses are usually heavily wooded, but elsewhere the vegetal covering is limited chiefly to coarse native grasses. Both the topography of the basin and the relative impermeability of the surface soils facilitate the rapid run-off of flood waters. Six major floods have occurred since 1854, but reasonably accurate information as to flood flow is available only for those of May 1929 and December 1935. During the former the indicated peak discharge from the 324 square miles of the Buffalo Bayou watershed above White Oak Bayou and from the White Oak basin of 114 square miles totaled 19,000 and 11,500 cubic

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feet per second, respectively, while the peak flow of Buffalo Bayou below the junction totaled 30,500 cubic feet per second. The corresponding discharges during the flood of 1935 were 40,000 cubic feet per second in Buffalo Bayou above White Oak Bayou, 16,750 cubic feet per second in the latter, and 53,000 cubic feet per second in the channel between White Oak Bayou and the turning basin. Flood damages occur chiefly in the wholesale commercial district of the city above Main Street, where encroachment of buildings, bridges, and other structures on the natural flood channel causes appreciably increased crest heights. Property losses within the city during the flood of 1929 were reported ~~by the Houston Chamber of Commerce~~ to total $1,392,442.76. The flood of 1935 inundated an area of some 2,410 acres within the city limits, including 25 blocks in the business and 100 blocks in residential sections; with property losses reported at $2,528,606.31. Above the city, some 20,000 acres of rural lands in the Buffalo Bayou watershed and 2,000 acres in the White Oak basin were flooded during 1935, but without appreciable damage. An overflow from the upper Buffalo watershed to Brays Bayou, which enters the ship channel from the southwest 2 miles below the turning basin, lessened flood heights within the city. No project for the control of floods on Buffalo Bayou has been authorized by Congress. In 1930–31 the city of Houston expended approximately $1,000,000 in the construction of a concrete-lined channel 1,300 feet long in Buffalo Bayou one-third mile above Main Street, with but limited benefit due to the restricted capacity of the channel below. Local drainage districts have expended $430,000 in the enlargement and rectification of the channel of Brays Bayou to increase its flood capacity; and approximately $100,000 in the similar improvement of Sims Bayou, which enters Buffalo Bayou from the southwest at the lower limits of the city.

4. Shoaling in the Houston Ship Channel is caused both by local bank caving, due largely to wave wash of passing vessels, and the deposit of sediment by tributaries. Bank caving cannot be prevented at reasonable cost but will gradually disappear with stabilization of side slopes. An analysis by the district engineer discloses that the main sources of troublesome silt deposits are the San Jacinto River above its junction with the ship channel and Buffalo Bayou above the turning basin. The greatest difficulty is experienced in and immediately below the turning basin. Excavation of the deep-draft ship channel caused a lowering of the general water level in this part of the bayou, with consequent increased slopes and velocities in the section above. Serious erosion of the bed and banks of the stream between White Oak Bayou and the turning basin has resulted; and most of the eroded materials are deposited in the basin itself due to the sudden diminution of current velocity at that point. Fill in the turning basin has averaged 4 feet annually during the past 8 years; and amounted to 8.56 feet during a 6 months' period including the flood of December 1935. Navigation is thus handicapped to varying degrees following major floods; but shipping operations can generally proceed without serious limitation after a few days of dredging.

5. The city of Houston has a population of 295,131. It is served by a network of railways and improved highways extending throughout Texas and adjoining States. The widely diversified commerce on the Houston Ship Channel has increased steadily from 12,000,414 tons

in 1927, to 23,800,415 tons, the maximum of record, in 1936. Vessel traffic during the latter year included nearly 22,000 round trips by steamers, motor vessels, barges, and tugs ranging in draft up to 31 feet.

6. Local interests in general request that the United States undertake measures for the control of floods in Buffalo and White Oak Bayous. Various plans have been suggested, including channel rectification and enlargement, diversion of flood waters around the city, and the construction of control works to prevent undue shoaling in and below the turning basin. Local authorities, the navigation district, and various civic associations have petitioned the State legislature for enactment of a bill creating a local flood-control district with authority to plan and execute works for flood control, reclamation, and the prevention of silt deposits in navigable streams, and to enter into contract with the United States for these purposes.

7. The district engineer notes that the flood of 1935 resulted from a 3-day rainfall averaging 15 inches on the watershed of Buffalo Bayou above White Oak Bayou and 12.7 inches in the White Oak Basin. Precipitations aggregating 21.11 inches in 24 hours and 33 inches in 3 days have been recorded in localities only 115 and 220 miles, respectively, from the center of the Buffalo Bayou watershed; and rainfall records for the entire State of Texas show a maximum average 3-day rainfall of 30.84 inches for an area of 300 square miles. Superimposing the latter on the Buffalo Bayou watershed above White Oak Bayou, which has an area of 324 square miles, and basing rainfall run-off relationships on an analysis and breakdown of the storm and flood of 1935, he arrives at a probable maximum crest discharge in Buffalo Bayou above White Oak Bayou of 89,350 cubic feet per second, provided overflow into the Brays Bayou watershed is prevented by artificial means. The corresponding discharge from White Oak Bayou is estimated at 45,000 cubic feet per second; while the combined discharge below the junction of the two streams is estimated at only 105,000 cubic feet per second due to the improbability of the phasing of the maximum crest flows in the two water courses. Little information is available by which to determine the probable periodicity of future floods, but from past records the district engineer assumes that the maximum probable flood will occur once and floods equivalent to that of 1935 will occur five times during the next 50 years.

8. The district engineer states that the cost of a system of works to afford complete protection to the Houston Ship Channel against siltage during floods would be unduly high. Both the complete diversion of the San Jacinto and the construction of control works near its junction with the ship channel were considered, but the required expenditures in either instance would far exceed the cost of removing the deposits by maintenance dredging as at present. Navigation is hampered most by shoaling of the turning basin through deposit of materials eroded from the light-draft channel immediately upstream. The prevention of such shoaling can best be accomplished as a part of a comprehensive plan for the control of floods in the tributaries above.

9. The district engineer has considered various plans for the control of floods on Buffalo and White Oak Bayous, including regulation by storage, diversion, channel rectification, and enlargement by excavation or by levees, and combinations thereof. Complete protection could be afforded by the construction of a canal diverting the flood

waters of Buffalo and White Oak Bayous direct to Galveston Bay, but the great length and necessarily large section of the new channels would entail excessive costs. Enlargement and rectification of the existing channels to afford capacity for the maximum probable flood would entail large quantities of excavation and the costly alteration or replacement of many bridges, as well as the design of special works to protect the Houston Ship Channel from deposits of silt. The watershed of Buffalo Bayou above Houston affords only one practicable reservoir site, the water courses being too shallow and the divides too low elsewhere in the basin for the creation of artificial storage at reasonable cost. A reservoir of 265,000-acre-foot capacity at this site, 26.8 river miles above the mouth of White Oak Bayou, could be regulated during the greatest flood to permit a maximum outflow of 15,000 cubic feet per second, which would be increased to 40,000 cubic feet per second at Main Street by inflow to the intervening reaches. A reservoir of 35,000-acre-foot capacity could be constructed on White Oak Bayou just north of the city limits, with a regulated maximum-flood outflow of 20,000 cubic feet per second at the dam site, increased to 30,000 cubic feet per second at the mouth of the bayou. Of the various possibilities investigated, the district engineer considers the most suitable plan to be the construction of the two reservoirs described, the enlargement of the channel in Buffalo Bayou between the western city limits and the mouth of White Oak Bayou to afford a constant capacity of 40,000 cubic feet per second, and the enlargement of the channel in White Oak Bayou to capacity increasing from 20,000 cubic feet per second at the proposed dam to 30,000 cubic feet per second at the junction with Buffalo Bayou. This improvement, called "plan I," would cost $6,721,880 for construction of the two reservoirs and the enlarged channels in the city of Houston, and $14,436,590 for right-of-way items, including land acquisition, modifications to bridges, buildings, railways, highways, sewers, etc. Included in the right-of-way items are over $6,000,000 for the purchase of 38,720 acres of land for the reservoir sites, and nearly $5,000,000 for 888 acres of land for channel improvements. Allowances for the reservoir sites are based on speculative values exceeding the actual values for farming or stock raising. The latter would be only partially impaired by the relatively infrequent overflow of the reservoir area, and the district engineer considers it equitable that the flood-control project be credited with the remaining value of the land, estimated at $25 per acre, or $968,000. The lands required for the channel improvement were credited with unit values ranging from $1,125 to more than $65,000 per acre, based on information submitted by the Houston Real Estate Board. Actually about one-third of the property affected has already been acquired by the city of Houston for park-development purposes, while other lands are included in the city's ultimate plans for park development and will eventually be purchased therefor in any event. As these lands would not be damaged but, on the other hand, would be improved for their intended recreational use by execution of the flood-control plan, the district engineer considers it equitable that the flood-control program be not burdened with the cost of their acquisition, estimated at $3,800,000. With these reductions, the district engineer arrives at a net cost of $16,400,000 for comparison with estimated benefits.

10. The district engineer evaluates the benefits of plan I at $44,000 per year through reduced Federal maintenance dredging costs, based on a 50 percent reduction in silt deposits from Buffalo Bayou; $450,000 annually within the next 50 years through avoidance of property damage in the city of Houston, which otherwise would total an estimated $10,000,000 for one occurrence of the maximum probable flood, and $2,500,000 each for five floods equivalent to that of 1935; $60,000 annually due to the prevention of interruptions to business; $33,000 annually through a 50 percent reduction in carrying charges on lands which must be held by the local navigation district for the deposit of materials dredged in the maintenance of the ship channel; $10,000 annually through the prevention of possible damages to warehouse stocks and other articles in storage at the port wharves and warehouses; and $50,000 annually through the prevention of such intangible damages as loss of life, disruption of commerce, and interruption of utilities. Assuming carrying charges at 6 percent for interest, maintenance, and amortization, the foregoing benefits, totaling $667,000 annually, would apparently justify a capital expenditure of $11,120,000. Further major benefits lie in an increase of some $5,000,000 in property values within the flood zone, which have been progressively devaluated as a result of past floods; and $1,000,000 through the betterment values of bridges to be replaced under the project, many of which are now in an advanced state of physical deterioration; bringing the total justifiable capital expenditure for flood-control purposes to $17,120,000. This sum compares favorably with the estimated net cost of $16,400,000. The district engineer accordingly recommends the adoption of a project embodying the general features of channel improvement and regulation set forth in plan I, at an estimated cost to the United States of $6,722,000 for construction items; subject in general to the condition that a responsible local agency undertake to furnish necessary rights-of-way and accomplish all other work included under the classification of right-of-way items, except that should the net value of such items for flood control exceed the estimated cost of construction items, the United States might pay one-half of such excess, the total Federal expenditure not to exceed $8,560,000.

11. The division engineer presents a modified plan of improvement, incorporating the detention reservoir on Buffalo Bayou as recommended by the district engineer; enlargement of the Buffalo Bayou channel between the western city limits and Main Street to a maximum capacity of 40,000 cubic feet per second; improvement of White Oak Bayou within the city limits to provide adequate flood openings through bridges, and levees where necessary to prevent overflow into Buffalo Bayou above Main Street, as well as the establishment of building lines and the prevention of dumping; improvement of the Buffalo Bayou Channel between Main Street and the turning basin to provide a discharge capacity of 70,000 cubic feet per second; and the construction of velocity-control works in the channel just above the turning basin. This improvement, which he designates "plan IV," would afford the same protection to the areas adjacent to Buffalo Bayou above Main Street as would plan I, while the proposed enlargement of the channel below Main Street and the velocity-control structure would further reduce erosion in the light-draft channel and lessen silting and channel velocities in the navigation improvement

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below. It eliminates the relatively expensive storage reservoir on White Oak Bayou and retains existing valley storage on that stream. While slightly higher flood levels in the upper reaches of White Oak Bayou may result, the division engineer believes that the savings in cost and the lessened rapidity of run-off into the main stream justify the change. Plan IV is estimated to cost roughly $9,000,000 for construction items. The division engineer states that except for land costs, which probably reflect speculative values, a substantial part of the total expenditures estimated by the district engineer under right-of-way items represents additions and betterments to existing streets, bridges, sewage systems, and other facilities, which may properly be classified as deferred maintenance, and reconstruction and modification of structures now encroaching upon the natural stream channel. Much of this work should be accomplished in the near future, regardless of the adoption of a flood-control project. Its cost, as well as that of necessary rights-of-way within the city limits, is fully justified by the resultant increased property values, without reference to benefits of the flood-control project. On this basis the division engineer reduces the estimated cost of right-of-way items to $3,075,500, bringing the total cost of plan IV to $12,075,500. The improvement would afford somewhat greater savings in annual maintenance dredging costs than plan I, increasing the capitalized value of annual damages to be prevented by the improvement to $12,167,000. Allowing an additional $100,000 for betterment of the light-draft ship channel and $5,000,000 for enhancement of property values, the division engineer finds that the total benefits should justify an expenditure of $17,267,000. He accordingly recommends the adoption of a project for improvement of Buffalo Bayou and its tributaries above the turning basin of the Houston Ship Channel in general accord with the features of plan IV, at an estimated Federal cost not to exceed $9,000,000, specifically limited to expenditures for the construction of channels and structures designed for flood-control and silt-prevention purposes; provided a responsible local agency with necessary authority to act for all parties other than the United States furnish necessary lands, easements, and rights-of-way, release the United States from any claims for damages, maintain and operate the works after completion, and establish and enforce building lines and prevent encroachments upon the channels as approved by the Secretary of War, who shall have final decision as to the type and adequacy of works for flood-control purposes and as to that portion of the cost of works serving dual purposes which may be properly chargeable to flood control.

## VIEWS AND RECOMMENDATIONS OF THE BOARD OF ENGINEERS FOR RIVERS AND HARBORS

12. The gradual encroachment of bridges, buildings, and other structures on the natural flood channel of Buffalo Bayou within the city of Houston has created a serious flood problem. The flood of December 1935 resulted in the loss of eight lives and property damage of several millions of dollars. Investigations by the district engineer disclose the likelihood of substantially greater floods in the future, with damages far in excess of any heretofore suffered. Navigation is handicapped during severe floods by extensive shoaling and high velocities in the upper reaches of the ship channel; and the already high

unit costs for maintenance dredging may be expected further to increase as the areas available for the deposit of dredged materials are exhausted. The Board concurs in the view that a substantial expenditure is justified for the alleviation of the flood problems of the city and port of Houston. Plan IV, as recommended by the division engineer, appears to offer the most effective solution for the combined problems of flood control and navigation at the locality. The details of a cooperative undertaking of this magnitude, many features of which must be coordinated with municipal or local plans not yet fully developed, should be left to the future determination of the Department. The Board therefore recommends the improvement of Buffalo Bayou and its tributaries above the turning basin of the Houston Ship Channel to provide for the control of floods, the protection of the city of Houston from flood damages, and the prevention of the deposit of silt in the turning basin of the Houston Ship Channel, by means of detention reservoirs, enlargement and rectification of channels, the construction of control works and any diversions which may be found advisable, at an estimated Federal cost not to exceed $9,000,000, specifically limited to the defraying of costs of construction of channels and structures designed for flood-control and silt-prevention purposes and excluding (a) the costs of all rights-of-way and flowage easements; (b) the costs incidental to the reconstruction, relocation, or modification of existing structures, bridges, buildings, railways, highways, utilities, and public and private facilities and properties of all kinds, except such as are integral parts of flood-control structures; and (c) the cost of that portion of flood-control channels or structures which is designed and constructed for other than flood-control purposes: *Provided*, That a single local agency be formed and vested with authority to act for, and in the name of, all interested parties, other than the Federal Government, in all matters pertaining to the formation, planning, financing, construction, and maintenance of the proposed project: *Provided further*, That the local agency aforesaid shall (a) provide without cost to the United States all lands, easements, and rights-of-way necessary for the construction of the project; (b) hold and save the United States free from damages due to the construction of such works; (c) maintain and operate all of the works after completion in accordance with regulations prescribed by the Secretary of War: *Provided further*, That the local agency will take such measures as may be necessary to (a) establish and enforce building lines approved by the Secretary of War for the protection of the floodway areas against further encroachments; (b) prevent further dumping of waste materials upon existing banks of streams or within said building lines; (c) give assurances satisfactory to the Secretary of War that the existing obstructions to, and encroachments upon, the stream channels within the city of Houston will be removed by and at the sole expense of the owner or local agency, as the initial step in the development of the adopted flood-control plan: And *provided further*, That the Secretary of War shall have final decision as to (a) the type and adequacy of plans for all works which function in whole or in part to serve flood-control purposes; (b) the portion of the cost of such works, designed and constructed so as to serve other than flood-control purposes, which is properly chargeable to the flood-control feature of the project.

For the Board:

G. B. PILLSBURY,
*Brigadier General, Corps of Engineers, Senior Member.*

## REPORT OF THE DIVISION ENGINEER

### SYLLABUS

Investigation of flood conditions and flood damages on Buffalo Bayou, in the city of Houston, and on the Houston Ship Channel show that serious flood damages which have been experienced in the past are due primarily to the flood crests and velocities resulting from the restriction of flood run-off by obstructions and encroachments upon the natural stream channel.

It is the opinion of the division engineer that the magnitude of the flood damages on Buffalo Bayou warrant improvement of this watershed by the Federal Government in the interest of flood control and navigation in accordance with the policies adopted by Congress in Public, No. 738, Seventy-fourth Congress (H. R. 8455). He is further of the opinion that the prevention of the deposition of silt in the turning basin of the Houston Ship Channel is desirable in the interests of navigation and can best be secured by the adoption of a flood-control project on Buffalo Bayou and its tributaries which provides for the protection of the city of Houston against flood damage and the control of flood discharge velocities to prevent bank erosion above the Houston Ship Channel turning basin.

The division engineer recommends that a flood-control project consisting principally of headwater control by a detention reservoir; enlargement and improvement of existing channels; and regulation of discharge velocities by control works near the turning basin of the Houston Ship Channel, be adopted at a cost to the United States of not to exceed $9,000,000, provided that local interests comply with all the conditions of cooperation stated herein.

War Department,
Office of the Division Engineer, Gulf of Mexico Division,
*New Orleans, La., May 29, 1937.*

Subject: Review of reports on Houston Ship Channel, Tex., and report on the control of floods on Buffalo Bayou, Tex.
To: The Chief of Engineers, United States Army.

### AUTHORITY

1. This combined review of reports on the Houston Ship Channel, Tex., and report on the control of floods on Buffalo Bayou, Tex., is submitted in compliance with instructions from the Chief of Engineers, dated March 3, 1936, and August 22, 1936, respectively, and under authority of a resolution adopted February 20, 1936, by the Committee on Commerce of the United States Senate, which reads as follows:

> *Resolved by the Committee on Commerce of the United States Senate,* That the Board of Engineers for Rivers and Harbors, created under Section 3 of the River and Harbor Act, approved June 13, 1902, be hereby requested to review the report on the Houston Ship Channel, Texas, submitted in Committee on River and Harbor Document No. 58, 74th Congress, first session, and previous reports, with a view to the improvement of said channels and their protection from the deposit of silt, consideration being given to the question of cooperation on the part of local interests.

and in accordance with the Flood Control Act of June 22, 1936, the pertinent part of which reads as follows:

> The Secretary of War is hereby authorized and directed to cause preliminary examinations and surveys for flood control at the following named localities:
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> *　*　*　*　*　*　*
>
> Buffalo Bayou, Texas.
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### SCOPE

2. This report covers flood control on the Buffalo Bayou watershed and protection of the Houston Ship Channel, from Morgan Point to the turning basin, from the deposit of silt.

GENERAL DESCRIPTION

3. *Location.*—Buffalo Bayou rises in eastern Waller County and western Harris County on the Brazos River divide and flows in a generally easterly direction to a confluence with the San Jacinto River. Thence the San Jacinto River flows southeasterly for 9 miles to Galveston Bay. The San Jacinto River drains an area of 3,927 square miles, including the Buffalo Bayou watershed which has a total area of 1,024 square miles, 438 square miles of which is located above the junction of White Oak Bayou with Buffalo Bayou at Main Street in Houston, Tex. The Houston Ship Channel extends from Bolivar Roads in lower Galveston Bay across the bay to Morgan Point, thence across San Jacinto Bay and through portions of the San Jacinto River and Buffalo Bayou to a turning basin in the city of Houston, a total distance of 50 miles. A light draft channel extends 6½ miles up Buffalo Bayou from the turning basin to the confluence of Buffalo and White Oak Bayous at Main Street, Houston.

4. *Topography.*—The watershed of Buffalo Bayou lies entirely within the Gulf Coast Prairie, a broad, almost level plain. The land surface rises gently toward the northwest with a slope of less than 3 feet to the mile. Irregularities in the surface topography are confined almost entirely to the valleys cut by the streams. Cover growth in this basin consists largely of coarse native grasses interspersed with a scattering growth of trees except along the stream banks which are usually quite heavily wooded. The topography of the basin furnishes little natural storage capacity for the retardation of run-off.

5. *Soils and drainage.*—Surface soils in the Buffalo Bayou Basin are outcrops of the Lissie and Beaumont formations belonging to the Quaternary system and consist of Katy fine sandy loam and Lake Charles clay. Both formations are poorly drained and in the natural state do not permit much percolation of surface water. Several drainage districts have been organized in this basin to improve these lands for agricultural use.

6. *Tributaries.*—The only important tributary above the Houston Turning Basin is White Oak Bayou which enters Buffalo Bayou about 22½ miles above its mouth. In the 16 miles below the turning basin numerous tributaries join the main stream, entering from both sides. The principal ones in their order upstream are: Greens Bayou, discharging from the north, and Sims Bayou and Brays Bayou flowing in from the southwest.

7. *Physical characteristics.*—Streams in the San Jacinto River and Buffalo Bayou watersheds have little or no flow during a considerable portion of the year but are subject to high flood stages, produced by surface run-off during storm periods. Tidal variation in Galveston Bay affects the lower reaches of these streams. Under normal conditions the mean and extreme tide ranges are: In lower Galveston Bay, 0.6 foot and 1.3 feet; in upper Galveston Bay, 0.6 foot and 1.3 feet; and in the San Jacinto River and Buffalo Bayou, 0.5 foot and 1 foot. Strong offshore winds, "northers", have depressed Galveston Bay as much as 2 feet below mean low tide; hurricanes have produced tides of 15 feet in Galveston Bay and severe storms over the drainage basin have resulted in rises in Buffalo Bayou and the San Jacinto River varying from 3 feet at Morgan Point to 40 feet at Main Street in Houston, Tex.

8. *Use of land.*—Buffalo Bayou flows through the center of the city of Houston and is joined in the commercial district of the city by White Oak Bayou. Brays Bayou also enters the main stream within the city and Sims Bayou forms its southeastern boundary. Brays Bayou, Sims Bayou, and the upper part of White Oak Bayou pass through residential sections where development has generally not extended to the banks. Buffalo Bayou and the lower part of White Oak Bayou traverse the business section of the city. The increasing value of lands in this commercial area has resulted in encroachment upon the flood plain of Buffalo Bayou by buildings adjacent to the channel and even over it. That portion of the watershed which lies above the city and the outlying residential developments is devoted principally to pasturage and general farming. The city of Houston, with a population of about 350,000, is the largest Gulf port west of New Orleans and the center of a highly developed system of railroads and highways.

9. *Bridges.*—There are no bridges across the Houston Ship Channel below the turning basin. Numerous bridges cross Buffalo Bayou and White Oak Bayou above the turning basin and present serious obstructions to the flow of floodwaters, particularly those bridges above the confluence of these streams. Paragraph 25 of the district engineer's report contains a tabulation of all bridges within the city of Houston and several above the city, with pertinent data thereon.

10. *Difficulties attending navigation.*—Under normal conditions vessels experience little or no difficulty in navigating the Houston Ship Channel. In time of flood, however, currents may be excessive and navigation difficult. Major floods on streams tributary to the ship channel cause large deposits of silt which tend to shoal the channel at certain points and limit the navigable depth. This is especially the case in the turning basin where normal conditions cannot be completely restored for a considerable period after the flood recedes although shipping operations can usually proceed without serious limitation after a few days of dredging.

11. *Maps and available data.*—Available maps of the Houston Ship Channel include United States Coast and Geodetic Survey Charts Nos. 532 and 1282. The United States Geological Survey topographic map of Harris County, on a scale of 2 inches to the mile, includes practically all of the watershed of Buffalo Bayou and a portion of the watershed of the San Jacinto River. Maps of the city of Houston or portions thereof are available at the engineering department of the city of Houston. The district engineer's report, appended hereto, is illustrated by the following maps and charts: Plate No. 1,[1] a general map of Buffalo Bayou and adjacent watersheds; plate No. 2, a topographic watershed map of Buffalo Bayou; plate No. 3,[1] a topographic map of the city of Houston and vicinity; plates Nos. 4 [1] and 5,[1] showing congested sections of the city of Houston; plate No. 6, profiles of Buffalo Bayou, White Oak Bayou, and Little White Oak Bayou; plates Nos. 7 to 11,[2] inclusive, showing details of three possible flood-control plans; plate No. A-1,[1] showing silt deposits or scour in the Houston Ship Channel; plate No. B-1,[1] showing development of basic rainfall formula; plate No. B-2,[1] showing discharge hydrographs, area distribution graphs, and pluviagraphs for Buffalo Bayou and White Oak Bayou.

[1] Not printed.
[2] Pl. 10 not printed.

### PRIOR REPORTS AND PROJECTS

12. *Prior reports.*—There are no prior reports on flood control on Buffalo Bayou, and no prior reports on the Houston Ship Channel with a view to its protection from the deposit of silt. Two reports considering improvement of the Houston Ship Channel in the interest of navigation have been submitted within the past 5 years. The first report, published in Rivers and Harbors Document No. 28, Seventy-second Congress, first session, was favorable to an increase of the depth and width of the ship channel. The second report, published in Rivers and Harbors Document No. 58, Seventy-fourth Congress, first session, was favorable to providing greater depth and width in the ship channel with suitable easing of bends.

13. *Existing project.*—There is no existing project for flood control on Buffalo Bayou. The existing navigation project for the Houston Ship Channel provides for a depth of 34 feet from deep water in Galveston Bay to and including the turning basin of the Houston Ship Channel, and widths of 400 feet through Galveston Bay, 300 feet from Morgan Point to a point 5,000 feet above Baytown, thence 250 feet to Norsworthy, and 200 feet from Norsworthy to the turning basin. The project also provides for suitable widening of the channel in front of the wharf at Manchester, for certain cut-offs and easing of sharp bends, for construction of a dike 26,000 feet long to protect the channel in upper Galveston Bay, and for a light-draft channel, 10 feet deep and 60 feet wide, along Buffalo Bayou from the turning basin to the mouth of White Oak Bayou in Houston. The work of deepening the channel from 32 to 34 feet as recommended by the Chief of Engineers in Committee on Rivers and Harbors Document No. 58, Seventy-fourth Congress, first session, is now under way. The total costs of the existing project for the improvement of the Houston Ship Channel to June 30, 1936, were: $9,165,869.79 for new work, including $1,365,000 from contributed funds, and $6,503,907.36 for maintenance.

14. *Local cooperation.*—In accordance with requirements of cooperation under the acts authorizing the existing and previous projects, local interests have made direct contributions of $2,771,297.83 in cash toward improvement and maintenance of the deep-draft section of the Houston Ship Channel and have provided all necessary rights-of-way and spoil-disposal areas. All other requirements of local cooperation specified under the acts authorizing the existing project and prior acts have been and are being fully met. In addition, local interests removed 1,592,330 cubic yards of material in enlarging the turning basin and providing berths at the municipal wharves, contributed $1,625.78 toward the cost of removing with Government plant the snags, logs, and other obstructions from the light-draft channel above the turning basin, and contributed $2,880.95 and 1,000 barrels of fuel oil toward the cost of dredging a light-draft channel from the Houston Ship Channel to the mouth of Goose Creek.

### OTHER IMPROVEMENTS

15. *Navigation.*—Improvements for navigation made by local interests consist of the following: Dredging the light-draft channel above the turning basin at a cost of about $45,000; dredging spur channels at Morgan Point, Baytown, Pasadena, and other points; and con-

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structing adequate terminal and transfer facilities as set out in paragraph 39 of the district engineer's report.

16. *Flood control.*—Local interests have made the following improvements for flood control: Constructed a concrete-lined channel in Buffalo Bayou from the Farmers' Market to Smith Street at a cost of about $1,000,000; and enlarged and rectified Brays Bayou, at a cost of about $430,000, and Sims Bayou, at a cost of about $100,000.

### COMMERCE AND VESSEL TRAFFIC

17. *Commerce.*—Commerce in the Houston Ship Channel has shown a progressive increase since the inception of the project. Tonnage carried over the waterway in the calendar year 1936 amounted to 23,800,415 short tons, with a value of $619,326,957. Of this commerce 9.65 percent was receipts, 80.90 percent shipments, and 9.45 percent local traffic. Foreign traffic accounted for 16.85 percent of the total tonnage. About 86 percent of the tonnage handled in 1936 consisted of oil and petroleum products; the remainder was miscellaneous commodities.

18. *Vessel traffic.*—Vessel traffic on the Houston Ship Channel during the calendar year 1936 amounted to 21,851 vessels with a net registered tonnage of 11,513,795 inbound, and 21,851 vessels with a tonnage of 11,501,941 outbound. None of the vessels using the channel drew over 31 feet; 27 had drafts of 31 feet; 22 had drafts of 30 feet; 197 had drafts of 28 to 30 feet; and the remainder drew less than 28 feet.

### FLOODS

19. *Characteristics of flood-producing storms.*—The storms which occur along Buffalo Bayou and its tributaries fall into two principal categories—cyclonic storms and thunderstorms. The thunderstorms are sometimes accompanied by excessive rainfall for short periods of time, but such periods are not of sufficient duration to result in major floods. Cyclonic disturbances, both tropical (hurricanes) and extratropical, are responsible for the storms of major extent and duration, being often accompanied by heavy rainfall for periods of from 2 to 5 days, and cause the major floods. The tropical cyclones, originating in the Tropics or in the Gulf of Mexico, usually approach the coast of Texas from the southeast and, upon encountering the greater frictional resistance of the land, curve to the northeast and pass up the Mississippi Valley; in this course they might readily pass directly over the watershed of Buffalo Bayou. The extratropical cyclones originate in the Pacific or on the western highland areas. Though they are usually centered over north Texas and Oklahoma as they travel to the east, they sometimes cause heavy rainfall along the Texas coast and might occasionally result in excessive rainfall on this watershed.

20. *Rainfall and run-off.*—The mean annual precipitation on the watersheds of Buffalo Bayou and the San Jacinto River is about 45 inches. The minimum annual precipitation during the period of record is about 18 inches and the maximum about 80 inches. A large departure from the mean is also evident in the case of monthly and daily rainfall. A characteristic of this portion of the country is its liability to storms of unusually heavy precipitation, which produce large stream discharges, often causing overflow and inundation

of a considerable overbank area. Records of stream flow are available for the West Fork of the San Jacinto River at Humble, Tex., since 1924; but no records are available for Buffalo Bayou except for the flood discharges of 1929 and 1935. Gaging stations were installed in Houston on Buffalo, White Oak, and Brays Bayous in 1936. It is expected that these gages will develop valuable information on future stream flow, but to the date of this report no information on flood discharge has been obtained from these stations. A comprehensive study of rainfall and run-off in this area is contained in appendix B [1] of the district engineer's report. (See also par. 22 below.)

21. *Flood frequency.*—There is no information available concerning floods on Buffalo Bayou prior to 1854. In the period between 1854 and 1937 six major floods have been recorded, one each in 1854, 1875, 1879, 1907, 1929, and 1935, or an average of one major flood every 13 or 14 years. The most destructive of these floods was that of December 1935.

22. *General discussion of floods and flood probability.*—No discharge records are available for Buffalo Bayou or White Oak Bayou prior to July 1936, and no data are available as to the discharges experienced during any of the floods except those of 1929 and 1935. Measurements made during these floods indicated peak discharges of 19,000 and 40,000 second-feet, respectively, for Buffalo Bayou above White Oak Bayou; 30,500 and 53,000 second-feet, respectively, in Buffalo Bayou below this junction; and 11,500 and 16,750 second-feet, respectively, in White Oak Bayou. Available information indicates that the stage reached in the city of Houston during the 1929 flood was equal to or greater than that of previous floods of record. In view of the fact that the preceding 20 years had seen material change in the stream channel and in the flood plain through the city where numerous bridges had been built and buildings had encroached not only on the flood plain but even on the deep and well-formed channel, thereby reducing its discharge capacity, it is impossible to make estimates of flood discharges prior to 1929. Lacking records and means of estimating previous flood discharges, it has been necessary to have recourse to an analysis of those Texas storms whose origins and characteristics have indicated a possibility of their reproduction on the Buffalo Bayou watershed, and a study of possible rainfall run-off conditions to determine the size of the floods for which protection should be provided. The method employed to establish maximum probable run-off from the watershed essentially consisted of an analysis and break-down of the storm and flood of 1935 to determine the salient features of the relation of run-off to rainfall on this particular watershed. The relationships so established were applied to the maximum probable storm considered as superimposed on the watershed area. Details of the investigation which resulted in the determination of the maximum probable run-off from this watershed are given in appendix B [1] of the district engineer's report. The conclusion is drawn from this investigation that the maximum probable run-off from the watershed of Buffalo Bayou would be about 89,350 cubic feet per second at a point just upstream from its junction with White Oak Bayou, if there were no overflow across the natural interstream divide into Brays Bayou, and a comparable figure of 45,000 cubic feet per second from the White Oak Bayou

[1] Not printed.

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watershed. Under existing conditions permitting overflow into Brays Bayou, the maximum probable combined discharge below Main Street is estimated at 90,000 cubic feet per second; but if the overflow into Brays Bayou were prevented by artificial works, the maximum probable combined discharge below Main Street is estimated at 105,000 cubic feet per second. It is estimated that a flood of these proportions might occur once in 50 years and that about five lesser floods similar to those hitherto recorded might be expected during the same period.

FLOOD DAMAGE

23. *Extent and character of area flooded.*—The flood of December 1935 inundated both urban and rural properties. In the city of Houston both Buffalo and White Oak Bayous left their banks, and their waters spread over an area of about 2,410 acres. This area, as indicated on plates 3 to 5[1] of the district engineer's report, included some 25 blocks in the commercial district and about 100 blocks in residential sections. Few of the properties were flooded to any great depth, but several commercial establishments bordering or built into the flood plain suffered heavy losses to both stocks and buildings. The obstruction to flow offered by buildings and bridges in the commercial district of Houston above Main Street, particularly between Milam Street and Capitol Avenue, was responsible for appreciable increase in flood heights and the heavy damages that resulted in the wholesale district which borders this area. Outside of the city limits an area of some 20,000 acres on the upper Buffalo Bayou watershed and an area of approximately 2,000 acres on White Oak Bayou watershed were flooded. These areas consist of farm lands, pastures, and woodlands. Crop losses during the 1935 flood were negligible because the flood occurred after the harvesting season. An overflow from the Buffalo Bayou watershed into that of Brays Bayou on the south increased the area flooded without doing appreciable damage.

24. *Interruption of routes of transportation.*—Major floods cause serious interruption to routes of transportation in the city of Houston. All railroads passing through the city cross either Buffalo Bayou or White Oak Bayou and major floods in these streams have caused interruption in service because of inundation or damage to bridge foundations. During the 1935 flood practically all traffic between the sections of the city separated by these bayous was suspended because all of the connecting vehicular bridges over Buffalo Bayou above its junction with White Oak Bayou and all but one across White Oak Bayou were under water.

25. *Loss of life.*—There are no available records of loss of life for the earlier floods, but the flood of 1929 resulted in the loss of one life and that of 1935 in the loss of eight lives.

26. *Estimates of flood damages.*—No comprehensive estimates of damages are available for floods prior to 1929. Current newspaper accounts placed the damages in the city of Houston resulting from the flood of 1875 at a million dollars. Similar accounts fixed the damages from the 1879 flood at $100,000. No estimates of damages for the 1907 flood, which was apparently somewhat smaller than the 1879 flood, are available. The flood of 1929, which is believed to have reached approximately the same stage at Main Street in Houston

[1] Not printed.

as that of 1879, caused much greater damages because of the greater development of the city within the flood plain. Reliable estimates place the property damages for the 1929 flood at $1,400,000 exclusive of those suffered by the port of Houston. The flood of December 1935 caused property damages estimated at $2,500,000 in the city of Houston. This flood, and that of 1929 to a lesser extent, caused extensive intangible damages in the city: Commerce within the city was disrupted; a serious fire and health hazard existed; and utilities were interrupted. The port of Houston was forced to be idle for a period of 3 days in 1935, and for a lesser period in 1929, because of excessive currents in the ship channel, and further delays were caused by silt deposits in the turning basin and the ship channel

SILTATION

27. *General.*—The deposit of silt in the Houston Ship Channel has been a matter of grave concern ever since the inception of the project. It has required recurrent maintenance dredging to prevent serious interference with navigation, and has thus involved the expenditure of large amounts of money. The scope of this report includes an investigation of the principal sources of this material, the quantities and locations of its deposit and ways and means of eliminating or appreciably reducing its amount.

28. *Sources.*—It is apparent that most of the sediment deposited in the channel is derived either from local bank caving or from silt brought in by the tributary streams. Bank caving or erosion resulting from wave wash, and from heavy rainfall, cannot be economically prevented, but this condition will largely stabilize itself when uniformity of channel cross-section is established and when the banks reach a stable angle of repose. Contribution of silt by the tributaries will probably continue indefinitely, but it is indicated that the greater part of this material is brought in by Buffalo Bayou and the San Jacinto River during flood periods. Silt control on Buffalo Bayou above the deep-draft turning basin and on the San Jacinto River above its junction with the ship channel would eliminate the major part of the silting in the ship channel.

29. *Erosion above the turning basin.*—A large part of the silt discharged into the turning basin from Buffalo Bayou comes from that part of the bayou below the mouth of White Oak Bayou. In this section the stream flows through a winding channel which has been improved to form the light-draft extension of the Houston Ship Channel. The artificial conditions introduced by widening and deepening the natural stream bed to construct the deep-draft ship channel have assisted in producing excessive velocities in the light-draft section and in thereby causing serious erosion. Computations based upon the changes in the cross-sectional area of this channel between Main Street and the turning basin from July 1928 to June 1936 show a net scour in this reach of 1,936,220 cubic yards.

30. The turning basin, a much enlarged and greatly deepened portion of the old channel of Buffalo Bayou, varies from 400 to 1,100 feet in width and has a surface area of approximately 50 acres. The great increase in width and depth experienced as Buffalo Bayou enters this area makes the turning basin a very effective stilling basin as indicated by the following figures showing the volume of silt deposited therein during the period under study:

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| Period | Cubic yards | Average fill |
|---|---|---|
| | | *Feet* |
| July 1928 to June 1935 | 1,834,270 | 21.37 |
| June 1935 to January 1936 | 734,810 | 8.56 |
| January 1936 to June 1936 | 81,240 | .95 |
| Total for period July 1928 to June 1936 | 2,650,320 | 30.87 |
| Average annual | 331,290 | 3.86 |

31. Appendix A[1] of the district engineer's report is a detailed analysis of the amount and location of silt deposited in the turning basin and in the Ship Channel during the past 8 years by the tributary streams. Net fill and scour which has occurred in the Ship Channel from the turning basin to Morgan Point is shown on a tabulation in this report. This tabulation gives the information for consecutive short reaches to show its distribution during a total average period of 7 years, 8 months and for two subperiods, from 1928 to June 1935, and from June 1935 to June 1936, to indicate, as far as possible, the effects of the 1929 and 1935 floods. The periods covered by the records for the several reaches vary from 7 years to 8 years and 5 months.

32. *Effects of floods on siltation.*—From the available data on the amount, location, and time of silting, the conclusion is drawn that the greater part of the silting in the Ship Channel can be attributed to floods in Buffalo Bayou and the San Jacinto River. For example, nine times as much silt was deposited in the turning basin during the period from June 1935 to January 1936, which included the December 1935 flood, as during the equal period from January 1936 to June 1936. Similarly, it was found that the rate of silting in the Ship Channel above the San Jacinto River was much greater during the period which included the flood of 1935 than during the previous period, while the rate of silting was greatest below the mouth of the San Jacinto during the period which included the maximum flood of record on the San Jacinto, that of May 1929.

## PLANS OF IMPROVEMENT

33. *Public hearing.*—For the purpose of enabling all interested parties to present their views concerning the proposed improvement for controlling floods on Buffalo Bayou and for prevention of the deposit of silt in the Houston Ship Channel, Tex., and to determine their willingness and ability to provide the necessary lands, easements, and rights-of-way that may be required for the execution of a flood-control plan, the district engineer held a public hearing in Houston, Tex., on December 9, 1936. Notices of the hearing were sent to all organizations, agencies, and persons believed to be interested. Appendix C[1] of the district engineer's report contains the record of the hearing together with all briefs submitted by interested parties.

34. *Improvement desired.*—Representatives of local interests present at the hearing were unanimous in desiring some form of flood control on Buffalo Bayou. However, they were not agreed as to the method of control. The several suggestions offered were as follows:

(*a*) The plan presented by engineering department of the city of Houston proposed the rectification and beautification of the channel of Buffalo Bayou from a point 1,500 feet west of Shepherd Drive (approximately 3.7 miles east of the

[1] Not printed.

western city limits) downstream to the turning basin. The plan proposes the use of a terraced earth section with paved sections where alteration of existing structures would be more expensive. It includes a structure at the lower end of the improvement to raise the floodwater elevation in the bayou above the turning basin so that noneroding velocities may be maintained for reduction of silt load. The estimated cost is given as $11,786,000.

(*b*) The plan proposed by the Harris County Houston Ship Channel Navigation District includes limited diversion of floodwaters from Buffalo Bayou at a point above the city, to Galveston Bay, and rectification of portions of the bayou within the city. The district also proposed a plan for complete diversion of the San Jacinto River and relocation of portions of the ship channel to protect the channel from silt carried by the San Jacinto River. Mentioned, but not advocated, was a plan of control by regulation of Buffalo Bayou, limited diversion of White Oak Bayou to Greens Bayou, and enlargement of the Houston Ship Channel to reduce flood velocities to 4 feet per second. No estimates of cost were given.

(*c*) The Buffalo Bayou Property Owners Association presented a plan which proposes rectification and enlargement of Buffalo Bayou from Sabine Street to the turning basin, with diversion of White Oak and Little White Oak Bayous to Hunting Bayou. This plan aims primarily at protecting private property from inundation. No cost estimates were given.

(*d*) A Mr. Serres presented a plan which proposes a general scheme of diversion.

35. *Local cooperation offered.*—No definite assurance has been given that the conditions of local cooperation required by the Flood Control Act of 1936, will be met. The city of Houston, the Harris County Houston Ship Channel Navigation District, and Harris County have presented a petition to the State Legislature of Texas for the enactment of a bill creating a central flood control authority. A copy of this petition, which forms appendix D [1] of the district engineer's report, indicates the general form of organization and method of financing which is proposed at this time by local interests. A bill, similar in purpose to the above petition, vesting certain authority in the Commissioners' Court of Harris County was passed by the current session of the legislature, but was vetoed by the Governor because of its tax remission features. It is understood that a similar bill, without the tax remission features, was recently passed by the legislature and signed by the Governor, but no copy of this act has yet been received.

36. *Possible plans.*—From a study of conditions on Buffalo Bayou and the Houston Ship Channel, it appears that the most feasible methods to be employed in a plan for flood control and silt prevention will consist of: (*a*) regulation of run-off by storage or detention reservoirs; (*b*) channel diversions; (*c*) enlargement and improvement of existing channels; and (*d*) control of discharge velocities, in such combinations as are most adaptable to the local conditions in various sections of the proposed project. Three general plans, designated as plans I, II, and III, the construction and cost details of which are shown on plates 7 to 11,[2] inclusive, and in appendix E [1] of the district engineer's report, have been prepared by the district engineer. The general methods of flood control upon which these plans are based and the principal features of each plan are as follows:

### PLAN I. REGULATION AND CHANNEL IMPROVEMENT

This plan provides for the construction of detention dams on Buffalo Bayou and White Oak Bayou and enlargement of the channels below these dams to accommodate the maximum regulated flow together with the run-off from the uncontrolled watersheds below the dams. It proposes a 265,000 acre-foot reservoir on Buffalo Bayou, 26.8 river-miles above its junction with White Oak Bayou,

[1] Not printed.
[2] Plate 10 not printed.

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the construction of a channel in Buffalo Bayou with a capacity of 40,000 second-feet from the western city limit to the junction with White Oak Bayou; a 35,000 acre-foot reservoir on White Oak Bayou near the northern city limit; and a channel in White Oak Bayou with capacity varying from 20,000 second-feet at the dam site to 30,000 second-feet at its mouth. This plan provides for no modification of the existing channel below the junction of White Oak and Buffalo Bayous at Main Street in Houston. The estimated cost of plan I is $21,158,470.

### PLAN II. DIVERSION AND CHANNEL IMPROVEMENT

This plan provides for the diversion of floodwaters from Buffalo Bayou at a point near the western city limit south and around the city to Galveston Bay and includes a leveed floodway to convey the floodwaters in Buffalo Bayou to the point of diversion and prevent their overflow into Brays Bayou; and rectification and enlargement of the channel of Buffalo Bayou from the point of diversion to the junction with White Oak Bayou, and the channel of White Oak Bayou through Houston. The estimated cost of plan II is $54,686,095.

### PLAN III. MODIFIED REGULATION, CHANNEL IMPROVEMENT AND VELOCITY CONTROL

The plan proposes a 135,000 acre-foot storage reservoir on Buffalo Bayou about 26.8 miles above its junction with White Oak Bayou; a channel with a capacity of 60,000 second-feet in Buffalo Bayou from the western city limit to its junction with White Oak Bayou; a channel in White Oak Bayou with a capacity of 45,000 second-feet; and a channel with capacity for 90,000 second-feet in Buffalo Bayou below the mouth of White Oak Bayou. This plan also includes a control structure in Buffalo Bayou above the turning basin designed to raise the floodwater levels and reduce velocities which would lessen erosion and the consequent silting in the ship channel. The estimated cost of plan III is $29,134,920.

37. *Other plans.*—Other possible plans considered by the district engineer, designed primarily to prevent silt deposition in the Houston Ship Channel, are as follows: Complete diversion of the San Jacinto River from a point above its junction with Buffalo Bayou to Galveston Bay; construction of control works in the San Jacinto River above its junction with Buffalo Bayou to restore the original regimen of the river and prevent further erosion of the stream bed; and construction of a settling basin on Buffalo Bayou just upstream from the turning basin.

## OTHER SPECIAL SUBJECTS

38. *Water usage.*—There is little sustained flow in the streams under consideration and, therefore, it would not be feasible to coordinate flood control with plans for the conservation or development of water resources for power, irrigation, or other purposes. Present usage of the streams is confined to the light draft navigation portion of Buffalo Bayou below Main Street.

## ECONOMIC DISCUSSION

39. The district engineer estimates that the average annual damages which would be prevented by suitable flood-control improvements, in accordance with plan I of his report, would amount to $667,000, itemized as follows:

| | *Average annual reduction in damages* |
|---|---|
| Property stock damage | $460, 000 |
| Losses to shipping | 20, 000 |
| Business suspension and wage losses | 60, 000 |
| Dredging costs (including spoil areas) | 77, 000 |
| Intangible damages | 50, 000 |
| Total reduction | 667, 000 |

Capitalizing this annual saving at 6 percent (4.5 percent for interest and 1.5 percent for maintenance and amortization) the district engineer estimates that the relief from flood damages would justify an expenditure of $11,120,000.

The district engineer estimates that there would be a further justification for the project in the enhancement of property values by $5,000,000 and that the replacement of the old bridges by new bridges would result in a betterment of about $1,000,000, under plan I, which is quite apart from the general question of flood control and should, therefore, be included as an additional benefit resulting from the flood control project. Summarizing the above items the district engineer concludes that the benefits of a flood-control project would justify a capital expenditure of about $17,120,000 as follows:

| | |
|---|---|
| (a) Average annual damages prevented capitalized at 6 percent | $11, 120, 000 |
| (b) Estimated enhancement of property values | 5, 000, 000 |
| (c) Estimated betterment value of new bridges | 1, 000, 000 |
| Total capitalized benefits | 17, 120, 000 |

## VIEWS AND RECOMMENDATIONS OF THE DISTRICT ENGINEER

40. *Views.*—The district engineer observes that conditions on Buffalo Bayou are such that floods cause large damages and that the maximum probable flood would probably cause tremendous damages to property in the city of Houston and result in excessive shoaling in the ship channel under present conditions. He believes that any plan which may be adopted should provide complete flood protection for the city of Houston, and that the deposit of silt carried by Buffalo Bayou into the turning basin and Houston Ship Channel should be provided against within practical limits. A comparison of the costs of construction of adequate silt control works with the cost of maintenance dredging as now practiced indicates that silt deposits in the ship channel which derive from the San Jacinto River can be removed most economically by dredging. The quantity of silt from Greens, Sims, and Brays Bayous is considered insufficient to warrant control works for its prevention. The district engineer believes that a plan including channel improvements and regulation would be the most feasible method of providing flood protection for the city of Houston and reducing silting in the Houston Ship Channel. He presents plan I embodying those general features as a suggested solution of the problem; but states that any project adopted should specify only the general features so as to permit elasticity in the perfection of final construction plans. The district engineer estimates the total cost of work under this plan to be $21,158,470. This estimate is subdivided into $6,721,880 for construction items, and $14,436,590 for right-of-way items. The district engineer points out that the latter figure includes $10,828,000 for the acquisition of land and $3,608,590 for the estimated costs of such items as relocating streets, removing buildings, relocating or rebuilding railroads, highways, bridges, and similar work involved in the proposed project. He further states that the item of $10,828,000 for land acquisition should be credited with the sum of $4,768,000 which is the estimated remaining asset value of the lands for other purposes after subjecting them to the requirements of flood control, in order to arrive at the proper charges against the flood-control project from the standpoint of its economic justification. The

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costs properly chargeable to the flood-control plan are, therefore, reduced to $16,390,470. The district engineer estimates the benefits to be derived from flood control under present conditions to be $17,-120,000 and states that flood damages will probably tend to increase with the continued development of the city unless flood control is provided. He, therefore, concludes that a comprehensive flood-control plan is economically justifiable.

41. *Recommendations.*—In view of the foregoing the district engineer recommends that a project embodying the general features of channel improvements and regulation be adopted for Buffalo Bayou, Tex., with a view to protecting the city of Houston and the Houston Ship Channel from floods at an estimated cost to the United States of $6,722,000 to cover the construction items as described in his report; provided that a responsible local agency will engage, under terms satisfactory to the Secretary of War, to furnish all of the necessary lands, rights-of-way, and easements and to do or to provide funds for doing all the work described in his report under the classification of right-of-way items; and provided further, that should the cost of the right-of-way items less credits for the asset value of these items for purposes other than flood control exceed the estimated cost of the construction items, the United States may pay one-half the cost of the said excess provided that the total cost to the United States including the estimated cost of the construction items may not be made to exceed the sum of $8,560,000 under this provision; and provided further, that the Secretary of War shall have final decision as to what portion of the cost of the right-of-way items is properly chargeable to the flood-control project.

## VIEWS OF THE DIVISION ENGINEER

42. *General.*—The division engineer concurs with the district engineer in his conclusions as to basic flood control data and general engineering methods for the solution of the flood problem that forms the subject of this report. He concurs specifically with the conclusions of the district engineer in paragraph 109 (b), (c), and (h) as to the necessity and economic advisability of furnishing effective protection to the city of Houston and the Houston Ship Channel from damage due to floods of a magnitude which can reasonably be expected to occur in the future. Analysis of the detailed plans and studies which are contained in the report of the district engineer indicates the complex nature of the various construction and financial features which must be balanced and coordinated in the formulation of an effective flood-control plan for the watersheds in question. The lack of agreement and the diversity of interests existing between the various local bodies and individuals concerned in securing protection against damage from floods is evidenced forcibly by the exhibits which comprise appendix C [1] of the district engineer's report. For this reason any plans submitted in this report should be considered as tentative. Final detail plans prepared by, or in cooperation with, an organized agency representing the local interests will be necessary in order to serve the interests of all parties concerned. Preparation of these plans may result in material modifications of present plans, particularly in the congested portion of the city of Houston.

[1] Not printed.

43. The rapid development and growth in importance of the city of Houston as a commercial and industrial center is indicated by the remarkable increase in shipping which has been experienced by the port of Houston during the past few years. Insofar as can be foreseen at this time this expansion will continue. Taking this factor into account in the evaluation of probable flood damages and the enhancement in property valuations which may be derived from, or contributed to, by an effective flood control project, any plan which would give less than complete protection should not be considered.

44. The silt prevention problem in the turning basin of the Houston Ship Channel will become a matter of increasing importance in the future, due to increasing difficulties and costs which will be experienced in securing spoil disposal areas within reach of dredging operations. From the standpoint of benefits to navigation and the Federal interest therein it is the conclusion of the division engineer that a flood-control project which will furnish the highest degree of protection against the deposit of silt in the turning basin should receive consideration in preference to plans which afford lesser degrees of protection.

45. *Plans proposed by the district engineer.*—The division engineer considers that the basic methods of flood control employed in the development of plan I and plan III by the district engineer offer the most practicable approach to the solution of the flood-control problem on the Buffalo Bayou watershed. In brief, plan I consists of detention reservoirs on Buffalo and White Oak Bayous and channel improvements on those bayous above their junction at Main Street in Houston. This plan provides for no improvement of the existing channel of Buffalo Bayou between Main Street and the ship channel turning basin. Plan III consists of a smaller detention reservoir on Buffalo Bayou and channel improvements to provide for estimated maximum flood flow on Buflalo and White Oak Bayous, including the channel of Buffalo Bayou below Main Street in Houston. This plan provides further for the construction of a velocity-control structure near the outlet of Buffalo Bayou into the ship channel turning basin.

46. *Plan proposed by the division engineer.*—The division engineer is of the opinion that a modified plan composed of what appear to be the most desirable features of plans I and III may offer a more effective solution of this flood-control problem for all parties concerned than either plan I or plan III. For the purpose of reference, this modified plan is designated as plan IV. The essential features of plan IV are as follows:

(*a*) A detention reservoir on Buffalo Bayou, similar to that proposed for plan I, having a storage capacity of 265,000 acre-feet and a regulated discharge of 15,000 cubic feet per second.

(*b*) Improvement of the existing Buffalo Bayou Channel between the city limits and Main Street in Houston, as in plan I, so as to provide for a maximum flood discharge of 40,000 cubic feet per second at Main Street.

(*c*) Improvement of White Oak Bayou within the city limits of Houston so as to provide building lines, prevention of dumping, adequate flood openings through bridges, and levees where necessary to prevent overflow from White Oak Bayou into Buffalo Bayou above Main Street.

(*d*) Improvement of Buffalo Bayou Channel between Main Street and the turning basin so as to provide for a maximum indicated flood discharge of 70,000 cubic feet per second.

(*e*) A velocity-control structure at the entrance of Buffalo Bayou into the turning basin similar to that proposed for plan III.

47. *General characteristics of construction involved in plan IV.*—

(*a*) *Channel sections.*—The method of channel treatment proposed for this plan is similar to that shown in the report of the district engineer for those sections of plans I and III which have been combined to form plan IV, except that work on White Oak Bayou has been limited to that necessary to restore and preserve the natural flood channel and prevent overflow into Buffalo Bayou above Main Street. Detail studies may show that terraced channel sections are more appropriate than trapezoidal sections in certain reaches of the streams where park developments are proposed. Economic considerations may justify the use of covered or partially covered channel sections in the congested downtown district of Houston.

(*b*) *Velocity-control structure.*—Determination of the exact type and details of the structure best adapted to regulate the discharge of Buffalo Bayou into the turning basin is dependent upon more detailed engineering and operating studies. On the basis of preliminary hydraulic studies a structure of the general type indicated on the sketch herewith (appendix F[1]) would appear to be satisfactory. Final determination of channel alinement, structure site, foundation conditions, and hydraulic details in connection with the preparation of detail plans may materially modify the present conception of this structure, but the estimated cost as included in the estimate for plan IV is believed to be adequate to provide for such changes as may be necessary.

(*c*) *Reservoir-regulation structure.*—Plans accompanying the district report have been prepared upon the basis of providing a regulating structure composed of three gate-controlled sluiceway units having a capacity of 15,000 cubic feet per second at high reservoir pool level. Maximum discharge would occur under a head approximating 40 feet, thus requiring three conduits with discharge areas of about 125 square feet each, depending upon details of design and losses. Manually operated stoney-type gates could be adapted to the type of operation required for this structure. Further study may show that an uncontrolled notch-type spillway warrants consideration for regulation of flow from this reservoir. Overtopping of the dam is provided against by the capacity of the freeboard, and which is equal to about 60 percent of the normal reservoir storage, as well as by oversize discharge conduits. The rainfall run-off factor used on this watershed is a further measure of protection against overtopping.

48. *Advantages of plan IV.*—The principal advantages which warrant the consideration of plan IV as compared to either plan I or plan III as viewed by the division engineer are:

(*a*) Plan IV would afford the same protection to the city of Houston on Buffalo Bayou above Main Street as is provided by plan I. This is considerably more than is afforded by plan III due to the larger capacity of the storage reservoir provided with consequent reduced flow for all floods. The maximum flood which must be routed through the city is held to 40,000 cubic feet per second for plan IV rather than 60,000 cubic feet per second which may occur under plan III.

(*b*) Plan IV would afford better protection below Main Street than either plan I or plan III. For plan I while the estimated flow would be somewhat less due to the reservoir on White Oak Bayou, the absence of any control structure above the turning basin would permit damaging velocities much more frequently with consequent danger to navigation and silting of the turning basin. As compared to plan III, plan IV would have a smaller flow in this reach for any particular flood due to the larger storage reservoir on the headwaters of Buffalo Bayou, and the omission of the enlargement of the channel in White Oak Bayou retaining natural storage and reducing the rapidity of run-off from that stream.

(*c*) Plan IV omits the expensive storage reservoir on White Oak Bayou (plan I) which is not economical at $119 per acre foot, and also omits the enlargement of channel on that stream (plan III) which only serves to accentuate the difficulties on Buffalo Bayou below Main Street by increasing the rapidity of run-off into the main stream. Although the result of these two omissions may cause slightly higher flood levels in the upper reaches of White Oak Bayou, it is believed that the benefits to be gained by enlarging this channel are not commensurate with the cost.

(*d*) In general, plan IV would provide the maximum possible regulation of flow on Buffalo Bayou above the turning basin so as to keep its discharge for all

[1] Not printed.

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possible floods within the capacity of the natural or designed channel and hold its velocities within such limits as would practically prevent erosion and danger to navigation in the turning basin.

49. *Cost and benefits.*—

(*a*) The estimated costs of the construction items submitted in the report of the district engineer are considered to be sufficient to provide for the development of the flood-control system proposed. Determination of the cost of lands and of the various kinds of construction work, which are classed under the heading of "Right-of-way items" in the report of the district engineer, presents a complicated problem within the city limits of Houston. Exclusive of the estimated costs of land, which very probably reflect speculative values in many instances, a very considerable portion of the costs which enter into the total expenditures required for right-of-way purposes represents work which may be classified as follows:

(1) Additions and betterments to existing facilities, such as streets, bridges, drainage and sewage systems. A portion of this work consists essentially of the replacement of obsolete or inadequate facilities. Certain items of this work could be properly classified as deferred maintenance. Expansion of existing facilities to serve the needs of a rapidly growing city forms a third and important element in the total expenditure required for work included under this category.

(2) Reconstruction and modification of structures so located as to restrict the natural stream channel. Structures falling within this classification are one of the primary causes of serious floods in the city.

(3) Improvements on properties in certain areas adjacent to the stream channels which have been seriously damaged by floods and which must either be demolished and removed, or materially modified as the case may be, to eliminate encroachment upon the natural stream channel.

(*b*) The division engineer is of the opinion that a large portion of the work which falls within the classifications mentioned above either must, or should, be performed in the near future by the owners regardless of the adoption of a flood-control project. The cost of the work would be also fully compensated for by the increased value of the properties repaired and reconstructed. A similar conclusion is reached in regard to the expenditures necessary for the acquisition of right-of-way areas within the city limits of Houston. The benefits and enhancement of property valuations which should accrue from the development of these areas for city park purposes as proposed by the local authorities, as well as the potential values afforded by these areas for the development of the air rights over the floodway in the congested section of the city, are believed to be more than sufficient to justify the expenditures involved, without reference to flood-control benefits. In the final analysis, considering the present status of the development of a flood-control project in the city of Houston, it is apparent that the economic justification of such a project is dependent to a large degree upon the determination of the benefits which will accrue not only from the protection afforded by the flood control works themselves but also from improvements such as city parks, better and more up-to-date buildings, bridges, streets, and public utilities made available in conjunction with the construction of the flood-control project. It is also true that, due to the complicated make-up of these benefits, their value is difficult to estimate and, at this stage of development of the project, largely a matter of opinion. In view of these circumstances, the division engineer is of the opinion that the problem of costs, damages, benefits, and economic justification of the proposed flood-control project in Houston may be simplified and placed upon an equitable basis for all parties concerned in the following manner:

(1) Expenditures required for the acquisition of lands within the city limits of Houston, and for all construction work necessary or desirable in conjunction with the making available of these lands for flood control and such other uses as may be desired by local authorities are believed to be justified from the standpoint of local improvements, without reference to subsequent benefits from flood protection. The total cost of this preparatory phase of the project should be borne by local interests and the economic justification of the expenditures involved should be determined by those interests.

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(2) Justification from an economic standpoint of all expenditures other than the foregoing which are found to be necessary for the construction of an effective flood-control program would then be dependent upon the evaluation of damages and determination of benefits in the usual manner without reference to the improvements discussed in the foregoing paragraph.

50. *Estimated cost and benefits for Plan IV.*—

*a.* The costs and benefits shown below are based upon the estimates contained in the report of the district engineer for plans I and III, modified to conform with the details of plan IV as set forth above. Allocation of costs and benefits are shown in accordance with the principles stated in paragraph 49, above.

FLOOD-CONTROL PROJECT

PLAN IV

(1) *Estimated cost.*—

| | Construction items | Right-of-way items | Total |
|---|---|---|---|
| (a) Buffalo Bayou—Reservoir | $1, 443, 500 | $3, 602, 000 | $5, 045, 500 |
| (b) Buffalo Bayou—City limits to Main Street—Channel enlargement and protection | 3, 265, 500 | (1) | 3, 265, 500 |
| (c) White Oak Bayou—19th St. to Main St.: | | | |
| Restore and protect natural stream channel | ----------- | (1) | ----------- |
| Construct levees to prevent overflow to Buffalo Bayou | 277, 500 | 100, 000 | 377, 500 |
| (d) Buffalo Bayou—Main St. to turning basin: | | | |
| Channel enlargement and protection including cut-offs | 3, 138, 500 | [2] 128, 500 | 3, 267, 000 |
| Velocity-control structure | 875, 000 | 60, 000 | 935, 000 |
| Total estimated expenditure | 9, 000, 000 | 3, 890, 500 | 12, 890, 500 |
| (e) Credit—Asset value of reservoir area | ----------- | 815, 000 | 815, 000 |
| Total estimated net cost | 9, 000, 000 | 3, 075, 500 | 12, 075, 500 |

[1] Cost offset by value of resulting improvements. (See par. 49.)
[2] All right-of-way items, except cost of land for cut-offs, are offset by value of resulting improvements.

(2) *Estimated benefits.*—

(*a*) Annual damages:

| | |
|---|---|
| Property and stock damage | $460, 000 |
| Losses to shipping | 20, 000 |
| Business suspension and wage loss | 60, 000 |
| Dredging costs | 80, 000 |
| Spoil area investment carrying charge | 60, 000 |
| Intangible damages | 50, 000 |
| Total annual flood damages | 730, 000 |

| | |
|---|---|
| (*b*) Annual damages capitalized at 6 percent | 12, 167, 000 |
| (*c*) Betterments to light-draft ship channel | 100, 000 |
| (*d*) Enhancement to valuation of properties adjacent to, but outside of, right-of-way areas | 5, 000, 000 |
| Total estimated benefits | 17, 267, 000 |

*b. Estimated cost of right-of-way items considered to be self-liquidating as public and private improvements without benefits derived from flood control*

| | |
|---|---|
| (*a*) Buffalo Bayou, city limits to Main St., land, bridges, buildings, streets, drainage, etc | $4, 422, 000 |
| (*b*) White Oak Bayou, 19th St. to Main St., reconstruction of highway bridges only | 715, 000 |
| (*c*) Buffalo Bayou, Main St. to Turning Basin, land, bridges, buildings, streets, drainage, etc | 4, 709, 000 |
| Total estimated cost | 9, 846, 000 |

*c. Recapitulation of estimated costs, benefits, and betterments from flood control and other related improvement work*

| | Estimated total cost | Estimated total benefit |
|---|---|---|
| 1. Flood control | $12,075,500 | $17,267,000 |
| 2. Improvements, other than flood control | 9,846,000 | [1] 4,654,500 |
| Total, Flood control and other | 21,921,500 | 21,921,500 |

[1] This benefit, representing approximately 50 percent of the estimated expenditures required for all rights-of-way and improvements in connection therewith in the city of Houston, is indicated as necessary in order to justify the costs resulting from this phase of the project. In view of the local conditions and considering that the greater portion of the costs for items other than flood control are 100 percent self-liquidating, it seems reasonable to assume that a benefit materially larger than that indicated as necessary will be derived from the project as a whole.

51. *Conditions precedent to the authorization of Federal participation on a flood-control project for Buffalo Bayou.*—

(*a*) *General.*—The primary cause of serious flood damage in Houston is the encroachment of bridges, buildings, and dumps upon the natural flood channel of Buffalo Bayou and its principal tributary, White Oak Bayou. Structures and properties so located are not only the cause of most of the trouble, but also are subject to the most serious flood damage. The removal or reconstruction of these structures so as to restore the natural flood channel is the first essential of any flood-control plan, and should be done at the expense of the owners or local interests, not only because such encroachments should never have been permitted, but also because the owners will receive full return, for any expenditures involved, in increased value of their property.

(*b*) *Local cooperation.*—In the opinion of the division engineer, the authorization of Federal funds for construction purposes on the flood-control features of any project which may be adopted for flood control on Buffalo Bayou and its tributaries should be made contingent upon the compliance by local interests with the conditions set forth below:

(1) *Flood-control agency.*—A single responsible agency should be organized under the State laws and empowered to act for all local interests in all matters pertaining to the flood-control project. This agency should be competent and vested with necessary authority for planning, financing, constructing, and maintaining the flood-control project insofar as all interests, other than Federal, are concerned.

(2) *Building lines.*—Building lines should be established along Buffalo and White Oak Bayous as may be necessary to prevent further encroachment of property development upon the present flood channels, or upon areas required for the development of the adopted flood-control project.

(3) *Dumpings.*—Steps should be taken, at the earliest practicable date, to prevent further dumping of waste materials within the present floodway channel or within the limits of the proposed flood-control channel.

(4) *Removal of encroachments.*—Existing encroachments upon and obstructions within the natural stream channels should be removed without cost to the United States.

(5) *Acquisition of right-of-way.*—Such measures as may be necessary to insure the availability of the necessary rights of way and flowage easements needed in the construction of the adopted flood-control plan should be provided without cost to the United States.

52. *Conclusions.*—In summation, the division engineer concludes:

(*a*) That due to the progressively increasing difficulties in disposal of dredging spoil, the protection of the turning basin of the Houston Ship Channel from the deposit of silt caused by floods on Buffalo Bayou can best be accomplished by a flood-control project which also affords effective protection to the city of Houston from damages due to floods on this stream.

(*b*) That the protection of the Houston Ship Channel above Morgan Point, from silt deposited by tributaries other than Buffalo Bayou is not economical as the deposits arising from these sources are relatively small and can be removed more economically by dredging than by the installation of protection works.

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(*c*) The maximum probable flood discharges on Buffalo and White Oak Bayous, shown below, have been determined by the rainfall run-off studies described in detail in the report of the district engineer, and are considered to be adequate to provide effective protection for any flood-control project on the streams under consideration.

| | Cubic feet per second |
|---|---|
| (1) Buffalo Bayou above junction with White Oak Bayou: | |
| (*a*) Under existing conditions with overflow permitted to Brays Bayou | 60, 000 |
| (*b*) With overflow to Brays Bayou stopped | 90, 000 |
| (2) White Oak Bayou above Buffalo Bayou | 45, 000 |
| (3) Buffalo Bayou below junction with White Oak Bayou: | |
| (*a*) With overflow permitted to Brays Bayou | 90, 000 |
| (*b*) With overflow to Brays Bayou stopped | 105, 000 |

(*d*) That the flood-control plan which provides the most complete degree of protection to the city of Houston and to the turning basin from ordinary floods, as well as from floods of great magnitude, should be given preference.

(*e*) That a flood control scheme based upon detention and regulation of head water run-off, improvement and enlargement of existing channels, and velocity control in the channel section above the turning basin offers the most effective solution for flood control on Buffalo Bayou and the prevention of silting in the Houston Ship Channel.

(*f*) That any adopted flood-control plan should be so designed and constructed as to permit the development of the floodway channels through the city of Houston for park purposes and that in the downtown district of Houston from the Farmers Market to San Jacinto Street a covered or decked-over floodway channel will probably permit the development of realty values in excess of the cost thereof.

(*g*) That the ultimate development of a workable engineering plan for any flood-control project on Buffalo Bayou and Houston Ship Channel is dependent upon the cooperation and coordination of local interests along lines similar to those stated in paragraph 51 hereof and that any authorization of Federal funds for this project should be made contingent upon the receipt of satisfactory assurances from local interests that the conditions set forth in that paragraph will be complied with.

(*h*) That plan IV as outlined herein, with such modifications as may be found advisable, appears to be the most practicable and effective plan and should be adopted for further detailed development.

(*i*) That the sum of $9,000,000, representing the estimated cost of construction of flood-control structures and channels for plan IV, is a fair estimate of the Federal interest in this project under existing congressional policies on flood control and navigation.

(*j*) That a flood-control project on Buffalo Bayou for the protection of the city of Houston and the prevention of silting in the Houston Ship Channel is economically justified.

53. *Recommendations.*—The division engineer recommends that a project be adopted for the improvement of Buffalo Bayou and its tributaries above the turning basin of the Houston Ship Channel, providing for the control of floods, the protection of the city of Houston from flood damages, and the prevention of the deposit of silt in the turning basin of the Houston Ship Channel, by means of detention reservoirs, enlargement and rectification of channels, the construction of control works and/or diversions, at an estimated Federal cost not to exceed $9,000,000, specifically limited for expenditure to the defraying of costs of construction of channels and structures designed for flood-control and silt-prevention purposes and excluding (*a*) the costs of all rights-of-way and flowage easements; (*b*) the costs incidental to the reconstruction, relocation, or modification of existing structures, bridges, buildings, railways, highways, utilities, and public and private facilities and properties of all kinds; and (*c*) that portion of the cost of flood-control channels or structures which are designed and constructed for other than flood-control purposes, *provided*, That a single local agency be formed and vested with authority to act for, and in the name of all interested parties, other than the Federal Government, in

all matters pertaining to the formation, planning, financing, construction, and maintenance of the proposed project; and *provided further*, That the local agency aforesaid shall: (*a*) provide without cost to the United States all lands, easements, and rights-of-way necessary for the construction of the project; (*b*) hold and save the United States free from damages due to the construction of such works; (*c*) maintain and operate all of the works after completion in accordance with regulations prescribed by the Secretary of War; And *provided further*, That the local agency will take such measures as may be necessary to: (*a*) establish and enforce building lines approved by the Secretary of War for the protection of the floodway areas against further encroachments; (*b*) prevent further dumping of waste materials upon existing banks of streams or within said building lines; (*c*) give assurances satisfactory to the Secretary of War that the existing obstructions to, and encroachments upon, the stream channels within the city of Houston will be removed by and at the sole expense of the owner or local agency as the initial step in the development of the adopted flood-control plan; And *provided further*, That the Secretary of War shall have final decision as to: (*a*) the type and adequacy of plans for all works which function in whole or in part to serve flood-control purposes; (*b*) the portion of the cost of such works, designed and constructed so as to serve other than flood-control purposes, which is properly chargeable to the flood-control feature of the project.

F. B. Wilby,
*Colonel, Corps of Engineers,*
*Division Engineer.*

## REPORT OF THE DISTRICT ENGINEER

### SYLLABUS

Investigation of dredging records for the past 8 years indicates that the principal sources of silt deposits in the Houston Ship Channel have been the San Jacinto River and the portion of Buffalo Bayou above the deep-water turning basin at Houston. A study of dredging costs, together with the delays and damages to shipping, indicates that, at the present time, maintenance of channel dimensions by dredging is more economical than the provision of works for silt control, except insofar as the latter might be incorporated in a general plan of flood control.

Investigation of the flood conditions in Buffalo Bayou shows that floods in the bayou above the deep-draft turning basin of the Houston Ship Channel constitute a menace to life and property in the city of Houston and a source of damage and inconvenience to the Houston Ship Channel. Analysis of rainfall and run-off conditions on this watershed indicates a possibility of floods with crest discharges more than 100 percent in excess of any that have been recorded to date. This report includes studies of plans for flood control and indicates that control by channel improvements and regulation would afford the most feasible comprehensive plan for the solution of the flood situation in Houston and alleviation of the problems arising from the deposit of silt in the turning basin of the Houston Ship Channel. The district engineer concludes that a capital expenditure of $17,120,000 may be justified on the basis of the prevention of flood damages and the general enhancement of property values. The district engineer finds that a comprehensive flood-control plan embodying channel improvements and regulation can be accomplished within the limit of the benefit, provided that expenses for the acquisition of lands be limited to the actual property damages caused by the flood-control works.

The district engineer accordingly recommends that the United States adopt a project for flood control on Buffalo Bayou, Tex., above the turning basin of the Houston Ship Channel, embodying channel improvements and regulation as its central features, provided that local interests shall comply with certain conditions of cooperation.

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WAR DEPARTMENT,
UNITED STATES ENGINEER OFFICE,
*Galveston, Tex., April 1, 1937.*

Subject: Combined review of reports on the Houston Ship Channel, Tex., and report on the control of floods on Buffalo Bayou, Tex.
To: The Division Engineer, Gulf of Mexico Division, New Orleans, La.

AUTHORITY

1. This combined review of reports on the Houston Ship Channel, Tex., and report on the control of floods on Buffalo Bayou, Tex., is submitted in compliance with instructions from the Chief of Engineers, dated March 3 and August 22, 1936; and in accordance with the following resolution adopted February 20, 1936, by the Committee on Commerce of the United States Senate:

> *Resolved by the Committee on Commerce of the United States Senate,* That the Board of Engineers for Rivers and Harbors, created under section 3 of the River and Harbor Act, approved June 13, 1902, be hereby requested to review the report on the Houston Ship Channel, Texas, submitted in Committee on River and Harbor Document No. 58, Seventy-fourth Congress, first session, and previous reports, with a view to the improvement of said channels and their protection from the deposit of silt, consideration being given to the question of cooperation on the part of local interests;

And in accordance with the Flood Control Act of June 22, 1936, which reads as follows:

> SEC. 6. The Secretary of War is hereby authorized and directed to cause preliminary examinations and surveys for flood control at the following-named localities:
>
> * * * * * * *
>
> Buffalo Bayou, Texas
>
> * * * * * * *

SCOPE

2. Original authority limited the scope of the investigation to the determination of ways and means of protecting the Houston Ship Channel from the deposit of silt, but later authorities have broadened the scope of this investigation to include the determination of ways and means of protecting the lands adjacent to Buffalo Bayou from inundation and damage due to floods in that stream. This report covers both matters in an inclusive flood-control study.

MAPS AND PLATES

3. Available maps of the Houston Ship Channel include United States Coast and Geodetic Survey Charts Nos. 532 and 1282 and various maps of this office. Available maps of the Buffalo Bayou watershed and the San Jacinto River watershed or parts thereof include United States Geological Survey topographic maps of Harris County, Tex., scale 1/31,680, 1915, various maps of the engineering department of the city of Houston, Tex., and tactical maps, Corps of Engineers, United States Army, scale 1/125,000. The following maps and drawings [3] are submitted with this report:

| Plate No. | Subject |
|---|---|
| 1. | General map. |
| 2. | Topographic watershed map. |
| 3. | Topographic map of city of Houston and vicinity. |

[3] Only plates Nos. 2, 6, 7, 8, 9, 11 printed.

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Plate No. Subject

4. Congested section in city of Houston.
5. Congested section in city of Houston.
6. Profiles—Buffalo Bayou, mile 31.68 to mouth of Brays Bayou; White Oak Bayou, mile 19.67 to mouth; Little White Oak Bayou, mile 13.41 to mouth.
7. Proposed dams, reservoirs, and rectified channels—flood control-plan I.
8. Proposed dam and reservoir on Buffalo Bayou—flood-control plan I.
9. Proposed dam and reservoir on White Oak Bayou—flood-control plan I.
10. Floodway diversion channel and rectification—flood-control plan II.
11. Proposed channel rectification—flood-control plan III.

A-1. Silt study—Total silt deposits (or scour) during average period of 7 years 8½ months prior to 1936 survey (to accompany appendix A).

B-1. Development of basic rainfall formula (to accompany appendix B).

B-2. Discharge hydrographs, area distribution graphs, and pluviographs for Buffalo Bayou and White Oak Bayou (to accompany appendix B).

## DESCRIPTION OF WATERWAY AND WATERSHED

4. *Description of waterway.*[4]—The Houston Ship Channel extends from Bolivar Roads in Galveston Bay across Galveston Bay and San Jacinto Bay (an arm of Galveston Bay) to Morgan Point and through portions of the San Jacinto River and Buffalo Bayou to and including the port of Houston, a total distance of 50 miles, with a light-draft channel extending 6½ miles up Buffalo Bayou from the turning basin of the port of Houston to a small turning basin at the confluence of Buffalo and White Oak Bayous at Main Street, Houston, Tex. Under ordinary conditions the mean and extreme tide ranges are: In lower Galveston Bay, 1.3 and 1.6 feet; in upper Galveston Bay, 0.6 foot and 1.3 feet; and in the San Jacinto River and Buffalo Bayou, 0.5 foot and 1 foot. The height of tide is influenced considerably by winds and storms; strong "northers" of the winter season have depressed the waters of the bay as much as 2 feet below mean low tide; hurricanes of summer and fall have caused tides of 15 feet in Galveston Bay; and the waters of Buffalo Bayou and the San Jacinto River, which ordinarily have little volume or effect, have, without seasonal restriction, caused rises of short duration varying from 3 feet at Morgan Point to 40 feet at Main Street, Houston, Tex.

5. The following-named waterways connect with the Houston Ship Channel at the points indicated:

| Name of connecting waterway | Point of junction | Project dimensions of connecting waterways (feet) | |
|---|---|---|---|
| | | Bottom width | Depth |
| Galveston Channel, Tex. | Bolivar Roads | 1,200 | 34 |
| Galveston Harbor, Tex. | do | 800 | 34 |
| Channel to Port Bolivar, Tex. | do | 200 | 30 |
| Louisiana-Texas Intracoastal Waterway, Tex. | do | 200 | 9 |
| Channel from Galveston Harbor to Texas City, Tex. | do | 300 | 32 |
| Cedar Bayou, Tex. | Morgan Point | 100 | 10 |
| Goose Creek Channel[1] | 2 miles above Morgan Point | 80 | 8 |
| Anahuac Channel, Tex.[1] | Trinity Bay | 80 | 4½ |
| Clear Creek, Tex. | Galveston Bay (upper) | 50 | 4 |
| Double Bayou, Tex. | do | 100 | 6 |

[1] No definite project dimensions; controlling dimensions given.

[4] Maps: U. S. Coast and Geodetic Survey Charts Nos. 532 and 1282 and plate No. 1 accompanied this report but plate 1 is not printed.

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6. *Geography and topography.*[5]—Buffalo Bayou rises in eastern Waller County and western Harris County on the Brazos River divide and flows generally east and south to the San Jacinto River. Above its junction with White Oak Bayou in the city of Houston its watershed has an area of 324 square miles. The stream flows through the city, dividing it into two parts of almost equal size, and is joined, in the center of the city and at the head of navigation of the Houston Ship Channel, by White Oak Bayou, with a drainage area of 114 square miles. From this point the stream flows through the light-draft section of the Houston Ship Channel, a distance of about 6½ miles, to the deep-draft turning basin. No large tributary streams exist in this reach. From the turning basin the Houston Ship Channel follows Buffalo Bayou 16 miles to its junction with the San Jacinto River. Numerous tributaries join the main stream along this reach and swell its drainage area to a total of 1,024 square miles. Thence the Houston Ship Channel follows the San Jacinto River 9 miles to Morgan Point, where it empties into Galveston Bay. The total watershed area of the San Jacinto River is 3,927 square miles, of which Buffalo Bayou and its tributaries contribute 1,024 square miles. The streams in the combined watersheds of Buffalo Bayou and the San Jacinto River have little or no flow during a large part of the year, but they are all subject to high flood stages due to surface run-off and in their lower reaches their stages are affected by tidal conditions in Galveston Bay.

7. The watersheds of Buffalo, White Oak, and Little White Oak Bayous lie entirely in the Gulf Coastal Prairie, a broad, almost level plain which is open and almost treeless except along the streams, where heavy growth usually exists. The plain of which these watersheds are a part rises gently from the coast line in a northwesterly direction on a slope of less than 3 feet to the mile. Almost the only irregularities in the general slope are the valleys cut by streams and, in the western part, many shallow depressions, varying in size from a few acres to a square mile or more.

8. *Geology.*—The geologic formations which outcrop on the watershed of Buffalo Bayou are of the Quaternary system; they are, successively, the Reynosa and Lissie sands, Beaumont clay, and recent deposits. These successive formations dip southeasterly in the same direction as the land surface, but on a much steeper slope; hence the older formations are found on the headwaters of the streams.

9. The Reynosa formation consists in general of 80 percent sand, 5 percent gravel, 10 percent clay, and 5 percent calcium carbonate. The Lissie formation is made up of about 60 percent sand, 20 percent sandy clay, 10 percent gravel, and 10 percent clay. The Beaumont formation consists of about 60 percent clay, 20 percent silt, and 20 percent sand.

10. The Reynosa and Lissie sands are important water-bearing horizons from which several large Gulf-coast cities and many individuals derive their water supplies. Overlain as they are by the Beaumont clay there is sometimes created enough artesian head to support flowing wells, though most wells, and particularly those which are included in large water-supply systems, must be pumped. The Beaumont clay is sometimes used in the manufacture of a fair

[5] Maps: U. S. Geological Survey—Topography of Harris County, Tex., 1/31,680 and pls. Nos. 1 and 2, accompanied this report but not printed.

grade of brick, but most of this clay has such a high shrinkage coefficient that it is unsuitable for this purpose.

11. *Soils.*—The soils of the Buffalo Bayou region represent the outcrops of the Lissie and Beaumont formations and consist, respectively, of Katy fine sandy loam and Lake Charles clay. In their natural state these soils support only a scattering growth of timber and are covered by coarse native grasses such as carpet grass, sedge grass, bear grass, and saw grass. The Katy fine sandy loam is generally poorly drained and this poor drainage is accentuated by the fact that it is underlain at depths of 2 to 3 feet by a tight fine sandy clay. The Lake Charles clay is also poorly drained and, due to its texture, does not, in the natural state, allow much percolation of water. Both soils are much improved by drainage, to provide which several drainage districts have been organized.

12. *Rainfall.*—The mean annual precipitation on the San Jacinto River and Buffalo Bayou watersheds averages about 45 inches, and the mean monthly precipitation is almost evenly distributed throughout the year. However, departures from the mean are large, and very high rates of rainfall are not unusual in this section of the United States. Thunderstorms and cyclonic storms, either tropical or extratropical, though often very local in extent, may produce excessive precipitation. Rainfalls of 23.11 inches in 24 hours, and 33 inches in 3 days have been recorded in localities only 115 miles and 220 miles removed from the center of Buffalo Bayou watershed. The maximum storms which have been noted on San Jacinto River watershed and Buffalo Bayou watershed were those of May 24–30, 1929, and December 6–8, 1935. Both produced floods, the former the greatest of record in the San Jacinto River and the latter the greatest of record in Buffalo Bayou. The rainfall during the storm of December 6–8, 1935, as obtained from semiofficial and unofficial records, averaged 15 inches on the watershed of Buffalo Bayou above its junction with White Oak Bayou, and 12.7 inches on White Oak Bayou watershed. A comprehensive study of rainfall in Texas is included in appendix B [1] of this report, from which it appears that the maximum probable rainfall which may occur on Buffalo Bayou watershed above White Oak Bayou is 30.8 inches in 72 hours.

13. *Run-off.*—Prior to July of 1936 only one stream-gaging station was in operation on the San Jacinto River watershed and none was located on the Buffalo Bayou watershed. The records from the installations of 1936 convey no valuable information because no heavy rainfalls have occurred during their short periods of operation. The gage on the West Fork of the San Jacinto River was installed in 1928 and continuous daily records (classed as poor) since October of that year are available. These records show a maximum discharge from 1,811 square miles of 111,000 cubic feet per second on May 31, 1929, and a minimum discharge of 14 cubic feet per second on September 8–10, 1931, clearly demonstrating the great fluctuations in discharge which characterize stream flow in this vicinity. From measurements and observations taken on Buffalo and White Oak Bayous during the floods of 1929 and 1935, it appears that the maximum crest discharges were, respectively, 19,000 cubic feet per second and 40,000 cubic feet per second in Buffalo Bayou above its junction with White Oak; 30,500 cubic feet per second and 53,000 cubic feet

[1] Not printed.

per second in Buffalo Bayou below White Oak; and 11,500 cubic feet per second and 16,750 cubic feet per second in White Oak Bayou. Investigation by area distribution graph method, as described in appendix B [1] of this report, indicates that the maximum probable crest discharge in Buffalo Bayou above White Oak Bayou would be 89,350 cubic feet per second were it possible for the stream channel to convey it to this point and the comparable maximum probable crest discharge in White Oak Bayou is 45,000 cubic feet per second. The investigation further indicates that, under existing conditions permitting overflow into Brays Bayou, the maximum probable crest flow in Buffalo Bayou below White Oak Bayou would be 90,000 cubic feet per second.

14. *Past floods*.—Records of past floods on Buffalo Bayou are singularly lacking. The only floods for which mention can be found are those of 1854, 1875, 1879, 1907, 1929, and 1935. Dr. S. O. Young in his "Thumb Nail History of the City of Houston" says that the first bridge over Buffalo Bayou was constructed at the foot of Preston Street in 1843 and was washed away by the flood of 1853 (1854) after which it was rebuilt with more clearance and longer approaches, only to be later destroyed by the flood of 1878 (1879). The Houston Daily Telegraph of September 19, 1875, and later dates stated that—

> On the 18th of September, Buffalo Bayou continued to rise up to 10 a. m. It reached a point higher than ever known by the oldest inhabitant. The White Oak Bridge was swept away, water reached the roofs of the houses and many shacks were seen floating down the stream. The flood continued and did not recede until September 26. A million dollars' worth of damage was done to the city. Lynchburg was swept away by an 8-foot tide and hurricane winds.

Extracts from the Galveston Daily News give the following information on the early floods:

> April 24, 1879: Another big rise like the one in 1875 is anticipated.
>
> April 25, 1879: It is conceded that such a volume of water has not passed down the stream since 1854, and never in the history of Houston has a flood been the cause of such destructive results.

An additional item which appeared on Sunday, April 27, 1879, fixed the damages from the flood at $100,000. It therefore appears that the stage of 1879 was equal to, or greater than, that of 1875, and less than the crest stage of 1854. A private photograph of the 1879 flood, with no accompanying description as to stage, shows, on landmarks which still exist, a stage at Main Street comparable to that attained in the 1929 flood.

15. There appears no further record of high water until that of May 1907 which available data indicate was somewhat less than the flood of 1929. Between 1907 and 1929 there were experienced several freshets, none assuming flood proportions. In the same interval there occurred many major alterations in and along the stream channel, which tended seriously to affect flood heights and thus to increase the susceptibility of various existing properties to flood damage and to create other properties susceptible to flood damage. These changes consisted of construction of the Houston Ship Channel and development of the port of Houston, thereby providing a channel of increased discharging capacity, which was liable to damage from silting and which in itself tended to aggravate this silting by engendering increased velocities in Buffalo Bayou above the main turning basin; and the construction in the city of Houston of many buildings and bridges which encroached not only on the flood plain of the stream but

also on the deep and well-formed channel, thereby reducing its discharging capacity. The inevitable consequence of these obstructions was that in May of 1929 a freshet of only 19,000 cubic feet per second crest discharge in Buffalo Bayou above White Oak Bayou was backed up to a stage that caused the loss of one life and damages estimated at about $1,400,000, exclusive of those suffered by the port of Houston. Shortly after this flood there was installed, in one of the sections of greatest congestion in the city of Houston, a high-velocity concrete-lined channel about 1,300 feet in length, which, however, was rendered ineffective inasmuch as the serious encroachments below this point were permitted to remain unaltered.

In December of 1935 there occurred a flood which exceeded all expectations and caused unprecedented damages. With a peak discharge in Buffalo Bayou, above White Oak Bayou, of 40,000 cubic feet per second, eight lives were lost and property damages in the city of Houston approximated $2,500,000. Both the 1929 and 1935 floods caused currents in the Houston Ship Channel which hindered navigation and caused deposits of silt therein which interfered considerably with shipping, so that damages of large extent, both tangible and intangible, were occasioned. Intangible damages were also sustained in the city of Houston. Buffalo Bayou traverses the heart of the city and a part of the wholesale commercial district was included in the inundated area, as were the numerous bridges which are part of the main commercial arteries of the city. In addition, one of the principal municipal pumping plants, which is located within the flood plain of Buffalo Bayou, was completely flooded and put out of operation. Thus in 1935, and, to a lesser extent, in 1929, there existed an effective disruption of commerce and a serious health and fire hazard, and the same situation must be expected in any future flood of comparable proportions unless extensive relocation or reconstruction of buildings and bridges be undertaken or unless a proper flood-control system be adopted.

16. *City of Houston.*—The area flooded in December 1935 included both urban and rural properties. In the city of Houston both Buffalo and White Oak Bayous left their banks, as indicated on plate 3,[1] inundating 2,410 acres of overbank area including about 25 blocks in the commercial district and about 100 blocks in residential sections. Most of the properties affected were not covered to any great depth but several commercial establishments bordering Buffalo Bayou or built in the flood plain thereof suffered considerable loss, both in damage to buildings and in damage to stocks. The principal cause of the inundation in the business section of the town was the obstruction of the waterway above Main Street by buildings, dumps, and bridges with insufficient vertical clearance and cross-sectional area. The most obstructed section of Buffalo Bayou, located between Milam Street and Capitol Avenue, is shown in plates 4 [1] and 5,[1] and the backwater effect produced by the obstructions during the floods of 1929 and 1935 is clearly shown by the profiles of plate 6. The major portion of the damages occasioned in the wholesale commercial district of Houston which borders Buffalo Bayou near this congested section may thus be attributed to encroachments upon the stream channel.

17. *Harris County.*—The area flooded in Harris County, exclusive of the city of Houston, amounted in December 1935 to about 20,000

[1]Not printed.

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acres of farm, grazing, and wooded properties on Buffalo Bayou and about 2,000 acres on White Oak Bayou. The damages suffered in the rural areas were practically nil due to the fact that the flood occurred after the harvesting season. An overflow from the Buffalo Bayou watershed to that of Brays Bayou to the south increased the area flooded without doing appreciable damage.

18. *Houston Ship Channel.*—The port of Houston was forced to be idle for a period of 3 days in 1935 and for a lesser period in 1929 because of strong currents in the ship channel. Upon subsidence of the floodwaters it was discovered that silt had been deposited in such quantities that the ruling depths for navigation were considerably decreased; in 1935 the greatest depth of deposits occurred in the turning basin, and in 1929 they occurred in that part of the ship channel which follows the San Jacinto River. (For silt analysis, see appendix A of this report.[1])

19. *Railroads.*—All railroads passing through Houston cross either Buffalo Bayou or White Oak Bayou and major floods in these streams have caused interruption of service, due either to the inundation of the bridges or to the washing out of pile bent approaches and pier foundations.

20. *Roads and bridges.*—During the 1935 flood both vehicular and pedestrian traffic between the two portions of the city were largely suspended. Every bridge across Buffalo Bayou above its junction with White Oak Bayou was submerged and every bridge but one across White Oak Bayou was completely flooded. Trolleys crossing the bayous could not operate and normal transportation generally failed. To cross Buffalo Bayou from the White Oak residential section to the business district of Houston required a 4-mile detour which was inconvenient and often impracticable.

21. *Future floods.*—In appendix B [1] of this report it is shown that the maximum probable future flood would far exceed in volume any flood that has been experienced to date. The crest discharge in Buffalo Bayou would reach 89,350 cubic feet per second at a point just above White Oak Bayou were it possible for the present channel to contain this flow. It is known, however, that overflow to Brays Bayou occurred in 1935 with a crest discharge of 40,000 cubic feet per second at the same point and it is therefore evident that greater overflow would occur under maximum storm conditions. The discharge hydrograph for Buffalo Bayou just below Turkey Creek (16 miles from the mouth of White Oak Bayou) reveals a crest discharge of 90,000 cubic feet per second in the maximum probable future flood. Of this amount there would be an overflow into Brays Bayou of 30,000 cubic feet per second under present conditions and a crest of 60,000 cubic feet per second could be expected to reach the city of Houston, producing higher flood stages then have yet been experienced. With a crest of 45,000 cubic feet per second in White Oak Bayou, as compared to the maximum crest of experience of 16,750 cubic feet per second, flood stages in White Oak Bayou would rise to a considerable extent and the overflow to Buffalo Bayou through the city of Houston would be much worse than the shallow overflow of 1935. Higher stages would cause increased damages in Houston since properties inundated in 1935 would be flooded to greater depth and many properties heretofore unaffected would be included in the flooded area.

[1] Not printed.

22. Little data are available for estimating the periodicity of future flood flow. Six floods have been recorded in Buffalo Bayou in a period of 80 years and thus tend to show an average periodicity of one flood per 10 years. The flood of 1935 was the greatest of definite record but there is such a difference between this flood and the maximum probable flood that it is likely that intermediate floods will occur. It may therefore be assumed that during the next 50 years there would occur the maximum probable flood and five floods averaging the size of the 1935 flood.

### TRIBUTARY AREA

23. The area tributary to the port of Houston includes the greater part of the State of Texas and portions of adjacent States. A highly developed system of railroads and highways makes Houston readily accessible from interior points. The area immediately tributary to the Houston Ship Channel includes the following communities:

| | *Population 1930* | | *Population 1930* |
|---|---|---|---|
| Houston and suburbs [1] | 295, 131 | Baytown | 5, 200 |
| Pasadena | 1, 647 | Pelly | 3, 452 |
| Deer Park | 50 | Goose Creek | 5, 208 |
| Deep Water | 50 | La Porte | 1, 280 |
| Lynchburg | 100 | | |

[1] Includes South Houston, West University Place, Stewart Heights, Sunset Heights, Bellaire, Channelview, Clinton, and Galena Park.

Houston is the largest port on the Gulf coast west of New Orleans. It enjoys a large foreign and domestic trade, the major portion of which is water-borne. Over 85 percent of its water-borne commerce is in oil, with cotton and foodstuffs next in order of volume.

24. *Population and industry.*—The following tabulation of census figures indicates the remarkable growth of population in the city of Houston since 1900:

| Year | Population | Year | Population |
|---|---|---|---|
| 1850 | 2, 396 | 1900 | 44, 633 |
| 1860 | 4, 845 | 1910 | 78, 800 |
| 1870 | 9, 382 | 1920 | 138, 276 |
| 1880 | 16, 513 | 1930 | 292, 352 |
| 1890 | 27, 557 | 1936 (estimate) | 350, 000 |

Comparable figures for the whole of Harris County in 1920 and 1930 were:

| Year | Total | Urban | Rural |
|---|---|---|---|
| 1920 | 186, 667 | 142, 356 | 44, 311 |
| 1930 | 359, 328 | 301, 012 | 58, 316 |

2



The industrial statistics for the city of Houston since 1919, also taken from official census reports, are as follows:

| Year | Value of products | Value added by manufacture | Year | Value of products | Value added by manufacture |
|---|---|---|---|---|---|
| 1919 | $86,874,480 | $29,082,240 | 1925 | $87,445,460 | $36,572,537 |
| 1921 | 73,745,403 | 26,305,229 | 1927 | 102,154,137 | 41,952,218 |
| 1923 | 84,501,970 | ------------ | 1929 | 145,049,659 | 65,278,485 |

The totals for Harris County for 1929, the only year for which comparable figures are available, are: Value of products, $285,227,185; value added by manufacture, $93,497,836.

### BRIDGES

25. There are no bridges across the channel from deep water in Galveston Harbor to and including the turning basin of the deep-draft section of the Houston Ship Channel. Ferries serve vehicular and pedestrian traffic at La Porte, Lynchburg, and Pasadena. Bridges above the deep draft turning basin are numerous and many present serious obstructions to the flow of flood waters, particularly those on Buffalo and White Oak Bayous in the city of Houston above the light-draft turning basin at Main Street. The following tabulation lists all bridges within the city of Houston and several upstream from the city on Buffalo and White Oak Bayous, giving pertinent data thereon, including the approximate clear opening or floodway:

*Bridges*

A. BRIDGES OVER LIGHT-DRAFT EXTENSION OF HOUSTON SHIP CHANNEL—ALL CONSTRUCTED UNDER PERMIT

| Miles upstream from the upper end of the turning basin | Owner | Name of bridge | Type | Approximate clear opening below roadway (square feet) | Use | Vertical clearance above mean low water (feet) | Horizontal clearance between piers (feet) |
|---|---|---|---|---|---|---|---|
| 0 | Galveston, Harrisburg & San Antonio Ry. (Southern Pacific). | | Swing | 11,400 | Railway | 34.1 | 128 |
| 0.7 | City of Houston | 69th St. | Bascule | 8,750 | Vehicular | 35.0 | 100 |
| 1.2 | Houston Belt Terminal Ry | | Swing | 8,000 | Railway | 35.5 | 103 |
| 2.9 | City of Houston | Lockwood Ave. | Lift | 8,910 | Vehicular | [1] 36.0 | 100 |
| 4.1 | San Antonio & Aransas Pass Ry. (Southern Pacific) | | Swing | 10,900 | Railway | 36.8 | 111 |
| 4.8 | City of Houston | Hill St.[2] | do | 7,460 | Vehicular | 36.0 | 123 |
| 5.0 | International-Great Northern Ry. (Missouri Pacific) | | Bascule | 9,660 | Railway | 30.0 | 91.4 |
| 5.3 | Gulf, Colorado & Santa Fe Ry. (Houston Belt & Terminal Ry). | | do | 8,060 | do | 38.0 | 80.5 |
| 5.6 | City of Houston | McKee St. | Fixed | 8,400 | Vehicular | 43.0 | 100 |
| 6.0 | Galveston, Houston & Henderson Ry | | do | 9,210 | Railway | 45.0 | 100 |
| 6.3 | City of Houston | San Jacinto St. | do | 6,900 | Vehicular | 38.8 | 110 |

[1] Raised 66.0 feet.
[2] Permit has been issued for replacement by fixed bridge having a clear height of 42 feet above mean low water for a channel width of 60 feet, and a clear height of 39 feet above mean low water for the clear width between piers, 110 feet.

NOTE.—The limiting vertical clearance from the deep-draft turning basin to Main St. is 38.8 feet. All railway bridges have pile-bent approaches.

B. BRIDGES OVER BUFFALO BAYOU ABOVE IMPROVED WATERWAY—ALL FIXED BRIDGES

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 6.4 | City of Houston | Main St. | Concrete arch | [3] 6,300 | Vehicular. | | |
| 6.53 | do | Milam St. | R. C. beam and slab | 2,125 | Do. | | |
| 6.67 | do | Franklin Ave. | R. C. beam and girder | 3,860 | Do. | | |
| 6.74 | do | Smith St. | do | 4,650 | Do. | | |
| 6.85 | do | Preston Ave. | do | 3,815 | Do. | | |
| 7.2 | do | Capitol Ave. | do | 10,225 | Do. | | |
| 7.6 | do | Sabine St. | do | 4,365 | Do. | | |
| 9.1 | Southern Pacific R. R. | Southern Pacific Bridge | Pile trestle and deck-plate girder. | 11,470 | Railway. | | |
| 9.6 | City of Houston | Waugh Drive | R. C. beam and girder | 6,140 | Vehicular. | | |
| 10.3 | do | Shepherd Drive | do | 6,330 | Do. | | |

| | | | | | |
|---|---|---|---|---|---|
| 18.5 | Southern Pacific | Eureka Cut-off | Pile trestle and deck-plate girder. | 5,125 | Railway. |
| 14.6 | Harris County | Post Oak Rd | Trestle concrete deck | 5,450 | Vehicular. |
| 22.9 | do | Hillendahl-Piney Point Rd. | do | 4,050 | Do. |
| 32.0 | do | Alief-Addicks Rd | Pile trestle | 1,400 | Do. |

[3] Clear opening below high-water surface of December 1935 (elevation 40, U. S. G. S.).

NOTE.—R. C. denotes reinforced concrete.

## C. BRIDGES OVER WHITE OAK BAYOU IN AND NEAR THE CITY OF HOUSTON—ALL FIXED BRIDGES [4]

| | | | | | |
|---|---|---|---|---|---|
| 0.04 | Southern Pacific R. R. | | Pile trestle | 4,025 | Railway. |
| 0.07 | Missouri, Kansas, & Texas R. R. | | do | 3,700 | Do. |
| 0.16 | City of Houston | Main St. Viaduct | Reinforced concrete | 6,200 | Vehicular and street railway. |
| 0.25 | Missouri, Kansas, & Texas R. R. | | Pile trestle | 4,100 | Railway. |
| 0.75 | do | | do | 19,610 | Do. |
| 0.9 | City of Houston | Crockett Ave | Reinforced concrete | 14,715 | Vehicular. |
| 0.95 | Missouri, Kansas, & Texas R. R. | | Pile trestle | 5,800 | Railway. |
| 1.5 | City of Houston | White Oak Drive | Reinforced concrete | 4,180 | Vehicular. |
| 1.7 | do | Houston Ave | Concrete trestle | 2,190 | Vehicular and street railway. |
| 2.7 | Houston Electric Co | Taylor St. Trestle | Pile trestle | 6,340 | Street railway. |
| 2.75 | City of Houston | Taylor St | Reinforced concrete | 1,900 | Vehicular. |
| 3.8 | Missouri, Kansas, & Texas R. R. | | Pile trestle | 5,440 | Railway. |
| 4.0 | City of Houston | Houston Heights Blvd | Reinforced concrete | 3,200 | Vehicular and street railway. |
| 4.1 | do | Yale St | do | 4,410 | Vehicular. |
| 5.8 | do | Shepherd Drive | do | 2,600 | Do. |
| 5.6 | Missouri, Kansas, & Texas R. R. | | Pile trestle | 4,580 | Railway. |
| 7.3 | Harris County | West 11th St | Wooden trestle | 2,900 | Vehicular. |
| 8.1 | do | West 19th St | Concrete deck, pile bents. | 3,030 | Do. |

[4] Miles upstream from junction of White Oak and Buffalo Bayous.

PRIOR REPORTS

26. Prior reports for the last 5 years on the Houston Ship Channel are listed below:

(a) Rivers and Harbors Document No. 28, Seventy-second Congress, first session, was favorable to (1) increase of depth to 32 feet throughout the deep-draft section, (2) widening of channel to 400 feet through Galveston Bay, 300 feet in the cut through Morgan Point, 200 feet thence to a point 4,000 feet above Baytown, and 150 feet thence to and including the turning basin, with suitable widening at the bends.

(b) Rivers and Harbors Document No. 58, Seventy-fourth Congress, first session, was favorable to providing for a depth of 34 feet from deep water in Galveston Bay to and including the Houston turning basin, with widths of 400 feet through Galveston Bay and 300 feet in the cut through Morgan Point, thence 300 feet to a point 5,000 feet above Baytown, thence 250 feet to Norsworthy, and 200 feet from Norsworthy to the Houston turning basin, with suitable easing of bends, all at an estimated cost of $3,400,000 for new work and $800,000 annually for maintenance of the entire project; provided local interests furnish, free of cost to the United States, necessary rights-of-way and release the United States from all claims for damage to private or municipal property due to the improvement and its maintenance.

27. Reports prior to those described above are listed in Rivers and Harbors Committee Document No. 28, Seventy-second Congress, first session. There are no prior reports on flood control of Buffalo Bayou.

EXISTING PROJECT

28. The existing project for the Houston Ship Channel provides for a channel 34 feet deep from deep water in Galveston Bay to and including a turning basin about 1,000 feet wide at the port of Houston, with widths of 400 feet through Galveston Bay, 300 feet in the cut through Morgan Point and to a point 5,000 feet above Baytown, 250 feet to Norsworthy, and 200 feet to the turning basin, with suitable widening of the bends at Lynchburg, Norsworthy, Manchester, and Harrisburg. The project also provides for suitable widening of the channel in front of the wharf at Manchester, for certain cut-offs and easing of sharp bends, for construction of a dike 26,000 feet long to protect the channel in upper Galveston Bay, and for a light-draft channel, 60 feet wide and 10 feet deep, without easing of bends, through Buffalo Bayou from the deep-draft turning basin to the mouth of White Oak Bayou in Houston, Tex. The latest approved estimate for annual cost of maintenance is $800,000.

29. The existing project was adopted by the following River and Harbor Acts: That of March 3, 1905, providing for the easing or cut-off of sharp bends and construction of the pile dike (R. and H. Com. Doc. No. 35, 61st Cong., 2d sess.); that of March 2, 1919, providing for a 30-foot channel, the widening at Manchester, and the present dimensions of the turning basin (H. Doc. No. 1630, 65th Cong., 3d sess.); that of March 3, 1925, providing for the light-draft extension of the channel to the mouth of White Oak Bayou (H. Doc. No. 93, 67th Cong., 1st sess.); that of July 3, 1930, providing for widening part of the channel and certain bends (H. Doc. No. 13, 71st Cong., 1st sess.); and that of August 30, 1935, providing for a 32-foot depth and widening of parts of the channel and certain bends (H. Doc. No. 28, 72d Cong., 1st sess.) and further providing for the 34-foot depth and widening of parts of the channel and easing bends (H. Doc. No. 58, 74th Cong., 1st sess.). The 32-foot depth was

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authorized by the Public Works Administration September 6, 1933, prior to its inclusion in the River and Harbor Act of August 30, 1935. The work of increasing the deep-draft channel dimensions as authorized is now under way. The total cost of the existing project to June 30, 1936, was $15,669,777.15, including $9,165,869.79 ($1,365,000 contributed funds) for new work and $6,503,907.36 for maintenance.

30. There is no existing project for flood control on Buffalo Bayou.

### LOCAL COOPERATION

31. *Navigation.*—In compliance with the provisions of the River and Harbor Act approved June 25, 1910, the citizens of Harris County, Tex., contributed the sum of $1,206,297.83, which was one-half of the cost, toward constructing the Houston Ship Channel to a depth of 25 feet; in accordance with the River and Harbor Act approved March 4, 1913, they contributed the sum of $200,000 toward the construction of two pipe-line dredges for the maintenance of the channel; and, in accordance with the provisions of the River and Harbor Act of March 2, 1919, they contributed $1,365,000 toward the cost of constructing a 30-foot channel. The city of Houston removed a total of 1,592,330 cubic yards of material in enlarging the turning basin and in providing berths at the municipal wharves. The total direct cash contribution toward improvement and maintenance of the deep-draft section of the Houston Ship Channel has thus been $2,771,297.83.

32. In 1913–14, the city of Houston contributed $1,625.78 (one-half the cost) toward the cost of removing with Government plant the snags, logs, etc., from the light-draft section of the Houston Ship Channel.

33. Local interests at Goose Creek and Houston contributed $2,880.95 and 1,000 barrels of fuel oil to the Government toward the cost of dredging a light draft channel from the Houston Ship Channel to the mouth of Goose Creek, which is tributary to the waterway and connects with it through Black Duck Bay about 2 miles above Morgan Point.

34. The River and Harbor Act approved March 3, 1925, in adopting the project for increased depth and width in Buffalo Bayou between the turning basin and the mouth of White Oak Bayou, provided:

> That local interests furnish free of cost to the United States all necessary rights-of-way and easements for construction and maintenance of all channels and for suitable dumping grounds during the construction and maintenance, and release the United States from all claims to private and municipal property due to the improvement and its maintenance, such as the undermining of banks, cracking of buildings, and injury to roads, walks, etc., from pipe-line flow.

35. The River and Harbor Act approved July 3, 1930, in adopting the modified project for increase in width of channel in certain places, provided:

> That local interests furnish without cost to the United States all necessary rights-of-way and easements and all necessary areas, suitably located, for the disposal of material excavated during the construction and maintenance of the channel, hold and save the United States from all claims for damages to private and publicly owned property due to improvement and maintenance of the channel, and deed to the United States without charge two plots of ground, one of about 3 acres on the west side of Morgan Cut and the other of about 1 acre on old Buffalo Bayou at Harrisburg.

36. The River and Harbor Act approved August 30, 1935, in adopting the modified projects for increases in depth, first to 32 feet,

then to 34 feet, and for increases in width and easing of bends, provides:

That local interests shall furnish free of cost to the United States suitable areas for the disposal of dredged material during construction and for future maintenance as and when needed (House Rivers and Harbors Committee Doc. No. 28, 72d Cong., 1st sess.), and;

That local interests furnish, free of cost to the United States, necessary rights-of-way and release the United States from all claims for damage to private or municipal property due to the improvement and its maintenance (House Rivers and Harbors Committee Doc. No. 58, 74th Cong., 1st sess.).

37. All requirements of cooperation specified under the acts authorizing the existing project and prior acts have been and are being fully met.

38. *Flood control.*—No definite assurance has been given that the conditions of cooperation required by the Flood Control Act approved June 22, 1936, will be met. The interested public parties, namely, the city of Houston, the Harris County Houston Ship Channel navigation district, and Harris County, have presented to the Legislature of the State of Texas a petition (appendix D) [1] for the enactment of a bill creating a central flood-control authority. It is understood that such a bill, vesting certain authority in the commissioners' court of Harris County, may be acted upon by the legislature at its current session.

## OTHER IMPROVEMENTS

39. *Navigation.*—In 1913–14 the city of Houston dredged the light-draft section of the Houston Ship Channel to a depth of 8 feet and a width of 40 feet, at a cost of approximately $45,000. Private interests have dredged spur channels at Morgan Point, Baytown, Pasadena, and other points. The Houston Ship Channel navigation district, the city of Houston, and private interests have provided the terminal and transfer facilities tabulated below. The facilities are considered adequate to accommodate present commerce.

[1] Not printed.

*Wharves*

A. PUBLIC WHARVES

| Wharf | Length, feet | Berthing capacity, vessels | Covered area, square feet | Open area, square feet | Railroad car storage | Material: Wharf | Material: Shed | Elevation mean low tide, mean low tide = −1 foot mean sea level |
|---|---|---|---|---|---|---|---|---|
| (1) LOCATED ON DEEP DRAFT CHANNEL | | | | | | | | |
| No. 1 | 823 | 2 | 85, 336 | 16, 048 | 83 | Creosoted pile | Concrete | 16. 5 |
| No. 2 | 522 | 1 | 53, 500 | 23, 190 | 55 | Concrete | Wood | 14. 5 |
| No. 3 | 799 | 2 | 51, 661 | 30, 300 | 60 | do | Steel and wood | 11. 0 |
| No. 4 | 777 | 2 | 60, 827 | 27, 841 | 73 | do | Concrete | 11. 0 |
| No. 5 | 80 | 1 | | 3, 680 | | Wood | Open | 11. 0 |
| Nos. 7 and 8 | 800 | 2 | 74, 166 | 20, 514 | 32 | do | Wood | 27. 0 |
| No. 10 | 600 | 1 | 72, 700 | 28, 338 | 61 | Concrete | Steel | 18. 0 |
| No. 11 | 530 | 1 | 66, 660 | 29, 160 | 65 | do | Concrete | 18. 0 |
| No. 12, 2-story | 530 | 1 | 95, 644 | 29, 260 | 60 | do | Concrete and steel | 18. 0 |
| No. 13 | 460 | 1 | 62, 176 | 32, 500 | 57 | do | Concrete | 18. 0 |
| No. 14 | 480 | 1 | | 49, 040 | 26 | do | Grain berth | 18. 0 |
| No. 15 | 480 | 1 | 65, 640 | 21, 830 | 48 | do | Concrete | 18. 0 |
| Manchester wharf (No. 75) | 500 | 1 | 86, 836 | 10, 000 | 30 | do | Steel | 17. 0 |
| Channel fuel dock (No. 77) | 253 | 1 | | 32, 295 | 20 | Wood | None | 18. 0 |
| Distribution warehouse | | | 201, 203 | | 82 | | Concrete | |
| Cotton concentration shed | | | 277, 163 | | 150 | | Wood | |
| Total | 7, 634 | 18 | 1, 261, 512 | 353, 996 | 902 | | | |
| (2) LOCATED ON LIGHT DRAFT CHANNEL | | | | | | | | |
| Main Street Wharf (No. 1) | 572 | [1] 4 | | 17, 600 | | Concrete | None | 11. 0 |

[1] Barges.

NOTE.—Wharves 7-8 and 13 are to be rebuilt.

*Wharves*—Continued

B. PRIVATE WHARVES

| Wharf owned by— | Length, feet | Berthing capacity, vessels | Material of wharf and shed, and principal cargoes handled | Elevation, feet above mean low tide |
|---|---|---|---|---|
| (1) LOCATED ON DEEP DRAFT CHANNEL | | | | |
| Armour Fertilizer Works, Ralston Purina Co. (using Armour wharf) | 150 | 1 | Creosoted timber fitted with hopper and conveyor for fertilizer and pipe line for molasses. | 17.5 |
| Houston Compress Co | 3,285 | 8 | Concrete apron track: Cotton and general cargo | 17.5 |
| Ship Channel Compress Co | 800 | 2 | Concrete: Cotton | 18.0 |
| Eastern States Petroleum | 150 | 1 | | 15.0 |
| American Maid Flour Mills (using Manchester wharf) | 500 | 1 | Grain-loading berth for elevator with 4 spouts | 17.0 |
| Carnegie Steel Co | 400 | 1 | Creosoted piling: Handling steel products | 20.0 |
| Southern Pacific Lines (Morgan Steamship Line) | 1,250 | [2] 3 | Concrete: General cargo | 20.0 |
| Manchester Terminal Corporation | 1,600 | 4 | Concrete: Cotton and general cargo | 17.5 |
| Coastal Oil & Transport Co | 150 | 1 | Creosoted piling: Oil wharf | 15.0 |
| Gulf Refining Co | 590 | 1 | Steel bulkhead: pile clusters, Oil wharf | 15.0 |
| Sinclair Refining Co | 1,400 | 3 | Concrete and creosoted piling: Oil pipe lines and case goods | 16.0 |
| Houston Lighting & Power Co | 150 | 1 | Creosoted piling: Oil wharf | 16.0 |
| The Texas Co | 1,400 | 3 | Steel bulkhead: Oil wharf | 15.5 |
| Champion Paper & Fibre Co | 200 | 1 | Creosoted piling, barge (completed July 1936) | 15.0 |
| Crown-Central Corporation | 300 | 1 | Creosoted piling: Oil wharf | 12.0 |
| American Petroleum Co | 150 | 1 | do | 14.6 |
| Shell Petroleum Corporation | 2,000 | [2] 3 | do | 15.0 |
| Gulf Pipe Line Co | 200 | 1 | do | 8.5 |
| Humble Oil & Refining Co | 1,400 | 4 | do | 12.3 |
| Total | 16,025 | 40 | | |
| (2) LOCATED ON LIGHT DRAFT CHANNEL | | | | |
| Merchants & Manufacturers Co.[3] | 250 | [1] 1 | Creosoted piling: General cargo | 7.0 |
| Prichards Rice Mill [4] | 120 | [1] 1 | Creosoted piling: Rice, etc | 8.0 |
| Southwestern Portland Cement Co | 380 | [1] 5 | Concrete: Shell and clay | 21.0 |
| Parker Bros., shell wharf | 252 | [1] 2 | Steel bulkhead shell wharf: Shell | 10.0 |

[1] Barges.
[2] Slip.
[3] Wharf connected to basement floor of Merchants & Manufacturers Bldg. by a tunnel.
[4] Not in use; only 38 feet serviceable.

NOTE.—Proposed, Shell Petroleum Corporation, extend slip and build 2 wharves 1,000 ft., 2 berths

40. *Flood control.*—The city of Houston in 1930–31, at an approximate cost of $1,000,000, installed a section of concrete-lined channel in the business district, from Farmers Market to Smith Street, designed to carry a flow of 34,000 cubic feet per second in Buffalo Bayou. Local drainage districts were formed on Brays and Sims Bayous to finance improvements to promote the rapid run-off of storm waters from these watersheds and to increase the capacities of the main channels. The enlargement and rectification of Brays Bayou, at a cost of about $430,000, and similar work on Sims Bayou, at an approximate cost of $100,000, have recently been completed.

## COMMERCE

41. The annual commerce on the Houston Ship Channel during each calendar year since 1904 is tabulated below. Commerce is listed in tons of 2,000 pounds and in value of this tonnage.

| Year | Tons | Value | Year | Tons | Value |
|---|---|---|---|---|---|
| 1905 | 104, 907 | $12, 544, 323 | 1921 | 2, 828, 460 | $78, 619, 629 |
| 1906 | 132, 108 | (1) | 1922 | 3, 365, 644 | 163, 887, 754 |
| 1907 | 452, 463 | 24, 466, 730 | 1923 | 4, 815, 119 | 252, 776, 363 |
| 1908 | 602, 734 | 28, 318, 621 | 1924 | 7, 094, 294 | 365, 851, 048 |
| 1909 | 1, 214, 904 | 36, 097, 560 | 1925 | 9, 732, 731 | 522, 429, 205 |
| 1910 | 1, 371, 650 | 39, 155, 357 | 1926 | 10, 359, 562 | 436, 469, 047 |
| 1911 | 1, 354, 897 | 34, 721, 530 | 1927 | 12, 000, 414 | 466, 316, 967 |
| 1912 | 1, 365, 050 | 35, 938, 800 | 1928 | 12, 981, 113 | 583, 541, 199 |
| 1913 | 1, 860, 452 | 38, 738, 464 | 1929 | 13, 917, 593 | 564, 842, 734 |
| 1914 | 1, 070, 700 | 24, 382, 700 | 1930 | 15, 536, 388 | 498, 658, 632 |
| 1915 | 1, 656, 347 | 31, 406, 916 | 1931 | 13, 971, 755 | 351, 782, 031 |
| 1916 | 1, 294, 309 | 32, 174, 971 | 1932 | 12, 710, 432 | 302, 862, 869 |
| 1917 | 1, 161, 424 | 35, 530, 279 | 1933 | 16, 928, 507 | 400, 875, 655 |
| 1918 | 2, 388, 066 | 116, 332, 138 | 1934 | 18, 516, 223 | 445, 555, 065 |
| 1919 | 1, 287, 972 | 85, 034, 834 | 1935 | 19, 774, 071 | 496, 902, 121 |
| 1920 | 1, 210, 204 | 102, 068, 452 | 1936 | 23, 800, 415 | 619, 326, 957 |

1 Not available.

42. The 1936 trade was divided as follows:

| | Receipts | Shipments | Total |
|---|---|---|---|
| | *Percent* | *Percent* | *Percent* |
| Foreign | 1. 95 | 14. 90 | 16. 85 |
| Coastwise | 6. 45 | 63. 60 | 70. 05 |
| Internal | 1. 25 | 2. 40 | 3. 65 |
| Local | | | 9. 45 |
| Total | 9. 65 | 80. 90 | 100. 00 |

The major portion of the increase in commerce in 1936 was coastwise trade.

43. Of the tonnage handled in 1936, about 86 percent consisted of oil and petroleum products. Other items, of which appreciable amounts were handled, were raw cotton, cotton linters, cottonseed meal, other cotton products, wool and mohair, scrap iron, manufactured metals, unmanufactured copper, pig iron, lead, carbon black, clay products, sulphur, molasses, sugar, salt, jute manufactures, cordage, corn, nuts, rice, flour, wheat, fertilizers and other chemicals, vegetables, canned goods, fruits, manufactured rubber, tobacco manufactures, linoleum, paper, furniture, lumber, cork manufactures,

glassware, automobiles, machinery, paints and varnishes, soaps, eggs, hides and skins, packing-house products, etc. Local commerce consisted mainly of traffic in oil, mud shell, sand, and gravel.

44. *Vessel traffic.*—Vessel traffic on the Houston Ship Channel for the calendar year 1936 is listed below:

*Trips and drafts of vessels*

IN-BOUND

| Draft | Steamers [1] | Motor vessels [1] | Barges | Tugs | Total |
|---|---|---|---|---|---|
| 28 to 30 feet | 7 | | | | 7 |
| 26 to 28 feet | 81 | 7 | | | 88 |
| 24 to 26 feet | 229 | 34 | | | 263 |
| 22 to 24 feet | 292 | 59 | | | 351 |
| 20 to 22 feet | 344 | 83 | | | 427 |
| 18 to 20 feet | 481 | 111 | | | 592 |
| Under 18 feet | 885 | 119 | 5,237 | 13,882 | 20,123 |
| Total | 2,319 | 413 | 5,237 | 13,882 | 21,851 |
| Total net registered tonnage | 8,505,105 | 1,586,598 | 991,750 | 430,342 | 11,513,795 |
| Passengers: | | | | | |
| Excursion | | | | | 7,028 |
| Regular [2] | | | | | 244 |

OUT-BOUND

| Draft | Steamers [1] | Motor vessels [1] | Barges | Tugs | Total |
|---|---|---|---|---|---|
| 31 feet | 19 | 8 | | | 27 |
| 30 feet | 11 | 12 | | | 23 |
| 28 to 30 feet | 156 | 34 | | | 190 |
| 26 to 28 feet | 450 | 107 | | | 557 |
| 24 to 26 feet | 363 | 82 | | | 445 |
| 22 to 24 feet | 297 | 68 | | | 365 |
| 20 to 22 feet | 274 | 47 | | | 321 |
| 18 to 20 feet | 215 | 23 | | | 238 |
| Under 18 feet | 514 | 48 | 5,237 | 13,882 | 19,681 |
| Total | 2,299 | 429 | 5,237 | 13,882 | 21,847 |
| Total net registered tonnage | 8,415,215 | 1,664,634 | 991,750 | 430,342 | 11,501,941 |
| Passengers: | | | | | |
| Excursion | | | | | 7,028 |
| Regular [2] | | | | | 137 |

[1] Includes 619 steamers, net registered tonnage of 2,189,690 tons, and 650 motor vessels, net registered tonnage of 2,398,975 tons, of foreign registry.

[2] 189 arrived and 44 departed on foreign vessels.

## DIFFICULTIES ATTENDING NAVIGATION

45. Under normal conditions, and with present project dimensions, vessels, loaded or light, should experience little or no difficulty in navigating the Houston Ship Channel. All curves of the deep-draft channel are eased to a least radius of 2,500 feet, and the channel is well marked and lighted so that under present traffic there is no necessity for further change in alinement or cross section. In time of flood, however, currents may be excessive and then navigation may be difficult until the major portion of the storm water has run off. Major floods in the streams tributary to the waterway cause large silt deposits which tend to shoal the channel at certain points and to limit the navigable depth until removed by dredging. This applies particularly to the turning basin, where normal conditions cannot be completely restored for a considerable period after a flood subsides, although shipping operations can usually proceed without serious limitation after a few days of dredging. An analysis of the deposit of silt in the Houston Ship Channel, which is included as appendix A[1] of this report, shows that the protection of the Houston Ship Channel

[1] Not printed.

3



from the deposit of silt from these sources can be accomplished only by control of floods on the San Jacinto River and Buffalo Bayou. The same is true of providing relief from velocities excessive for safe navigation. These questions will be considered at greater length in the general discussion.

### IMPROVEMENT DESIRED

46. At a public hearing held in Houston, Tex., December 9, 1936 (record attached as appendix C),[1] the various views of interested public agencies and individuals were expressed. All agreed that some form of control of floods in Buffalo Bayou was necessary but not all agreed as to method of control. The following suggestions were received:

(*a*) The engineering department of the city of Houston submitted a brief (appendix C, exhibit 2)[1] which includes a plan for channel rectification and beautification of Buffalo Bayou from a point 1,500 feet west of Shepherd Drive (approximately 3.7 miles east of the western city limits) to the turning basin. This is stated to be a preliminary estimate for one of the several methods of control to be considered. The plan is based on an assumed 3-day rainfall of 20 inches uniformly distributed over Buffalo Bayou watershed. The estimated peak discharge is given as 50,000 cubic feet per second in BuffaloBayou above its junction with White Oak Bayou, an increase of 25 percent over maximum recorded experience; and 60,000 cubic feet per second in Buffalo Bayou below its junction with White Oak Bayou, an increase of less than 14 percent over maximum recorded experience. The plan proposes the use of a terraced earth section conforming in general to existing ground slopes, with the introduction of paved rectangular or trapezoidal sections at points where the destruction or replacement of existing structures would be very expensive. It includes a structure at the lower end of the improvement the purpose of which is to raise the floodwater elevation in Buffalo Bayou just above the turning basin and thus decrease surface slopes above this point so that a noneroding velocity may be maintained for protection of the ship channel from the deposit of silt. The plan provides for lowering the flood peak at Main Street to elevation 36 on the city datum or approximately 32 feet above mean sea level. The estimated maximum cost of the plan is $11,786,000.

(*b*) The Harris County Houston Ship Channel navigation district submitted a brief (appendix C, exhibit 3)[1] outlining a plan for protecting both the city and the ship channel from floods. This plan includes limited diversion of the floodwaters of Buffalo Bayou from a point above the city of Houston south and around the city to Galveston Bay, thus entirely avoiding the Houston Ship Channel, and rectification of portions of Buffalo Bayou within the city of Houston to handle the remaining flow. There was also outlined a plan for complete diversion of the San Jacinto River and the relocation of portions of the Houston Ship Channel to protect the channel from silt carried by the San Jacinto River. Mentioned, but not advocated, are control of Buffalo Bayou by regulation, limited diversion of White Oak Bayou north of Houston to Greens Bayou, and enlargement of the Houston Ship Channel to reduce the velocity during floods to 4 feet per second. It is stated that higher velocities are hazardous to navigation. No estimate of cost was given for any of these projects.

(*c*) The Buffalo Bayou Property Owners Association submitted a brief (appendix C, exhibit 5)[1] which offered a plan for rectification and enlargement of Buffalo Bayou from Sabine Street to the turning basin of the Houston Ship Channel, together with diversion of White Oak and Little White Oak Bayous north of Houston to Hunting Bayou. This plan is designed primarily to protect private property from inundation.

(*d*) Mr. Serres presented an individual paper in favor of a general scheme of diversion (appendix C and exhibits 6 and 7).[1]

The chamber of commerce, Houston, Tex., and the Houston Electric Co. submitted letters to emphasize the need for flood control (appendix C, exhibits 4 and 8).[1] None of the plans other than that of the Engineering Department of the City of Houston includes estimates as to future probable flood flow or rainfall. All plans are general in character and unite only in expressing the desire that something be accomplished to afford relief.

[1] Not printed.

DISCUSSION

47. The appendices to this report develop the facts that there may be expected rainfall of considerable magnitude on the watersheds tributary to the Houston Ship Channel and that the maximum probable flood of any tributary has not been experienced within the period for which records are available. Under present conditions such maximum floods would undoubtedly produce tremendous destructive effects and deposits of silt in the Houston Ship Channel far in excess of any that have been encountered to date. In order to protect the Houston Ship Channel completely from the deposits of silt by all tributaries there would be required a system of works that would be expensive in the extreme. It therefore appears reasonable to restrict the field to only those tributaries which have caused the greatest deposits in the past, namely, the San Jacinto River and that portion of Buffalo Bayou above the turning basin. Each of these streams presents a separate and distinct problem and therefore each will be considered individually.

48. *San Jacinto River.*—The San Jacinto River drainage basin covers an area of 2,903 square miles above its junction with Buffalo Bayou. In flood the river proper occupies a flood plain from 1½ to 2½ miles wide for some distance just above its junction with Buffalo Bayou. (See U. S. Geological Survey map of Harris County, Tex.) Below this point it debouches into a broad delta and floods numerous bays and shallows on its 9-mile journey to Galveston Bay, leaving in its path large deposits of silt which vary in quantity with the size of the flood. These deposits of silt reduce the navigable depth of the Houston Ship Channel and thus impede navigation, although floods which have caused deposits in quantities which have seriously interfered with navigation have been few. The continued growth of the commerce of the port of Houston is a most pointed indication that the deposit of silt causes but a temporary discomfiture to shipping and that while losses, both tangible and intangible, have undoubtedly been occasioned, their magnitude has not been enough to prove a deterrent to the use of the channel. The Harris County Houston Ship Channel navigation district has suggested control of the San Jacinto River to avoid deposit of silt by its floodwaters in the Houston Ship Channel and has proposed diversion through wide channels dredged in the Delta as the most satisfactory means of control. It is believed that the proposed diversion channels in the Delta would reduce the silting in the Houston Ship Channel to some extent but that the deposit of silt would not be reduced in proportion to the additional cross-sectional area provided. It would be necessary, in order to insure effectiveness of the diversion, to maintain the diversion channels, and thus the problem of maintenance would probably be as large an item as at present, and the only advantage of the proposed project would be some abatement of the interference with navigation caused by the deposit of silt in the Houston Ship Channel.

49. Another plan has been considered for reducing the silt load brought into the ship channel from the San Jacinto River. This plan involves the use of control works at some point in the lower reach of the river above its junction with the ship channel, with a view to preventing the further degrading of the bed of the stream to meet the new base level established by the enlargement of the lower

2



end of the river for navigation. This plan would probably be much cheaper to put into execution than the proposed diversion but it would be open to the following objections: (1) It would interfere with navigation on the San Jacinto unless costly navigation works were provided, and (2) it would restore the original higher flood stages at points above the control works and thus possibly interfere with flood-control and drainage problems on this part of the river. Despite these disadvantages it is believed that control works for restoring the original regimen of the river would probably be the best means of relieving the silt deposits from the San Jacinto River in the ship channel. However, it is believed that dredging is by far the most economical means of solving the silt problem at this locality at this time and that the construction of control works should be deferred until the cost of maintenance may have increased sufficiently to justify the expenditure for other means of control.

50. *Buffalo Bayou.*—Buffalo Bayou drains a watershed of 1,024 square miles. This watershed is composed of tributary watersheds as follows:

| | *Area square miles* |
|---|---|
| Buffalo Bayou above White Oak Bayou | 324 |
| White Oak Bayou | 114 |
| Brays Bayou | 148 |
| Sims Bayou | 80 |
| Greens Bayou | 203 |
| Minor tributaries and area contributing directly to main stream | 155 |
| Buffalo Bayou total | 1, 024 |

51. Of these streams Buffalo, White Oak, and Brays Bayous pass through the city of Houston, and the lower part of Sims Bayou forms its southeastern boundary. Greens Bayou joins Buffalo Bayou and the Houston Ship Channel from the north about midway between Brays Bayou and the San Jacinto River.

52. No public agencies have requested improvement of Greens, Sims, or Brays Bayous or any of the minor tributaries. No floods have been experienced on Greens Bayou which have caused embarrassment to shipping and no great deposit of silt in the Houston Ship Channel from this source has been disclosed by the survey of this office (appendix A).[1] There is practically no development other than agricultural on this watershed, but progressive programs have caused improvement of drainage facilities even to the increase of capacities of the main streams. It is believed that under present conditions losses from flood in the Greens Bayou area would not be large. In paragraph 40 above, the improvements of Brays and Sims Bayous were mentioned. These improvements have increased the capacities of these streams so that all but extraordinary floods can be contained within banks. Both streams pass through residential districts wherein development has not extended to the immediate banks. It therefore appears that overflow, which could be expected only infrequently, would not cause large losses under present conditions, but there can be little doubt that future growth of Houston will lead ultimately to serious encroachment on the banks of these streams unless definite measures for preventing encroachment are instituted and enforced. High water carries silt in considerable quantities from Brays Bayou into the Houston Ship Channel, but apparently deposits little from

[1] Not printed.

Sims Bayou. To decrease the deposit of silt from Brays Bayou would require either (1) an installation at the lower end to raise the water level and thus decrease surface slopes, preventing the development of excessive velocities, or (2) some method of control to reduce the discharge in the stream during floods. However, no investigation of Brays and Sims Bayous or their watersheds has been made, since it has not been requested by local interests and since improvements for flood control, mentioned above, have recently been completed on both streams.

Detailed investigation is therefore limited to a consideration of flood control and silt control on Buffalo Bayou above the turning basin of the Houston Ship Channel.

53. Buffalo Bayou above the turning basin presents an entirely different picture from its lower tributaries. Buffalo Bayou above White Oak Bayou, draining a watershed of 324 square miles, traverses a portion of the commercial district of a city of a population of about 350,000 and is met in the heart of the city by White Oak Bayou, which conducts the storm drainage from 114 square miles through one of the residential districts, and the combined discharge of the two streams flows on through the light-draft extension to the turning basin of the Houston Ship Channel. The value of lands in the business district of Houston has kept pace with its growth. This increasing valuation of lands has resulted in the filling in of low lands adjacent to the stream and to the further encroachment upon the waterway by the construction of buildings adjacent to the channel and even over it. In addition to these encroachments the majority of the vehicular bridges over Buffalo and White Oak Bayous above their junction have been constructed with inadequate floodway openings. These obstructions on and over the waterway can render what would have been a harmless flood under the natural regimen of the stream a serious menace. But even had natural channel conditions remained undisturbed the danger of flood would still be present because the natural capacities of the stream channels are insufficient to accommodate within banks the great flood flows which may be produced by major storms on the watersheds. Hence it appears that the problem cannot be completely solved by the mere removal of the obstructions. Prime factors in limiting stream capacities are the small cross-sectional areas afforded in stream valleys, the winding courses followed by the streams, and the heavy growths of trees and underbrush which obstruct the flow. The small natural capacities of the streams were demonstrated by the overflow which occurred in 1935 in the agricultural areas upstream from the city of Houston. Damages in the rural areas were not great, due to the fact that there could be little crop loss in December, but the potentialities of future flood flows were clearly manifested. It is to be expected that excessive rainfall on the flat areas of this watershed will, in itself, cause much damage to crops. This damage could be lessened by adequate drainage. The provision of such drainage on Buffalo Bayou watershed would be a large undertaking because of the large quantity of run-off which must be provided for. If land drainage were installed on the headwaters of the stream, it would decrease the time of concentration of flood waters and thereby tend to increase flood stages. But below the confluence of the headwater streams, land drainage probably would not increase maximum flood stage, since it would tend to hasten the run-off of local waters before the arrival of the main crest.

54. From the mouth of White Oak Bayou to the turning basin, Buffalo Bayou flows through a winding channel which is used by the light-draft extension of the Houston Ship Channel. The artificial conditions introduced by man in widening and deepening the natural stream bed to construct the Houston Ship Channel have assisted in causing the development of excessive velocities in the light-draft section, and have thereby assisted in causing serious erosion of bed and banks of the stream. The eroded material is carried to the turning basin where the transporting power of the water is lost in a sudden diminution of velocity with the result that a great accumulation of silt occurs. Since the wharves and allied facilities of the port are centered here, the sudden loss of depth and blocking of the basin temporarily interrupts commerce until normal conditions are gradually restored. The embarrassment caused by the sudden cessation of commerce is very temporary, since little time need be lost before the institution of dredging operations, and these soon clear away enough of the obstruction to allow business to proceed with only slight inconvenience. It has been pointed out in appendix A[1] that the chief source of the silt which is deposited in the turning basin is that section of Buffalo Bayou between Main Street and the turning basin and that the cause of the erosion in this reach is the excessive velocity which is attained here by flood waters. Obviously, then, the complete protection of the turning basin from the deposit of silt would require primarily that erosion in the light-draft section of the Houston Ship Channel above the turning basin be stopped, and any reduction of erosion in this reach would furnish a corresponding modicum of relief in the silting of the turning basin. Major floods in Buffalo Bayou also render navigation in the Houston Ship Channel difficult by creating high velocities in the ship channel itself, and thus, apart from the deposit of silt, are a hindrance to shipping interests. The only effective means to remove this hindrance is to curtail flood flow from Buffalo Bayou so that excessive velocities are not created in the Houston Ship Channel. Further widening of the ship channel now in progress will alleviate this condition.

55. Any plan which would protect properties in and above Houston from inundation and flood damage, and which would prevent the deposit of silt and the creation of excessive velocities in the Houston Ship Channel would provide a complete solution of the Buffalo Bayou flood problem.

56. The brief submitted by the engineering department of the city of Houston contains estimates for a plan of rectification and enlargement of Buffalo Bayou to accommodate an estimated maximum flood flow of 50,000 cubic feet per second above White Oak Bayou and 60,000 cubic feet per second below. Other than the statement that these flows are expected to result from a 3-day rainfall of 20 inches distributed uniformly over the watershed, the basic premises are not stated. It appears from the studies made in appendix B[1] of this report that both these estimates of maximum probable rainfall and maximum probable discharge are too low; and particularly does the assumption of a contribution to the crest of but 10,000 cubic feet per second from White Oak Bayou appear too conservative, especially when it is considered that there was a contribution of 13,000 cubic feet per second to the peak of the lesser flood of December 1935. As regards the suggested improvements below White Oak Bayou, which are designed to protect the Houston Ship Channel from the deposit of silt

[1] Not printed.

by maintaining a maximum average velocity of 4 feet per second between White Oak Bayou and the turning basin, there are several points to be considered. A maximum average velocity of 4 feet per second would certainly produce less erosion than the average velocities of 6 to 11 feet per second which were experienced in 1935. However, a reduction in velocity would necessitate a proportionate increase in cross-sectional area, since no control of quantity is contemplated, and, therefore, the control of velocity includes not only the cost of the velocity-control structure but also the cost of an appropriate channel enlargement between that structure and the limits of appreciable backwater effect at Main Street, Houston. The capital expenditure necessary to protect the Houston Ship Channel from the deposit of silt from Buffalo Bayou and to lower the maximum stage at Main Street to 32 feet mean sea level is placed by the engineering department of the city of Houston at $6,661,667, of which $250,000 represents the cost of the velocity-control structure. The estimate of maximum probable crest flow in the channel between Main Street and the turning basin, on which this plan is based, is very low, and the cost of channel rectification with similar velocity to provide for greater discharge would be greatly increased.

57. The brief submitted by the Harris County Houston Ship Channel Navigation District suggests a combination of diversion and rectification. By this plan all flood waters of Buffalo Bayou in excess of that quantity which would not cause erosion or velocities in the Houston Ship Channel excessive for navigation would be diverted south and around the city of Houston to Galveston Bay, intercepting Brays and Sims Bayous. This plan would obviously provide protection for all. No estimates are included in the brief.

58. The brief submitted by the Buffalo Bayou Property Owners' Association is apparently predicated on the assumption that appropriate channel enlargement to accommodate the flood flow of December 1935 would afford relief from inundation of private and public properties. Reference to appendix B[1] of this report indicates that such provision would be inadequate. The cost estimates contained in the brief are, consequently, too low. The partial diversion of White Oak and Little White Oak Bayous north of the city of Houston to Hunting Bayou would have little effect on lowering flood crests along White Oak Bayou, because of the small diversion channel provided, and the provision of a larger channel for this diversion would result in the transfer of the flood problem from one locality to another.

### POSSIBLE MEASURES OF RELIEF

59. *General.*—The several possible methods of control of floods on upper Buffalo Bayou and on White Oak Bayou are (1) regulation by storage, (2) diversion of flood waters through artificial channels, (3) rectification and channel enlargement by excavation or by levees, and (4) combinations of regulation, diversion, and rectification.

60. *Regulation of Buffalo Bayou.*—The topography of Buffalo Bayou is such that no outstanding reservoir sites are afforded. The headwater tributaries of the stream flow through parallel shallow valleys of small capacity and heavy rainfall invariably results in overflow. As the tributaries later converge and join, the valleys become progressively deeper and better defined, though still of a capacity

[1] Not printed.

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that is readily overtaxed by the run-off from major storms. The watershed then narrows and the stream flows through a channel which is very close to the Brays Bayou divide on the south of the watershed, thence continuing into Houston and to its junction with White Oak Bayou. On only one short reach are there any practicable reservoir sites. Below this section, because of the narrowness of the watershed, artificial storage could be created only by the construction of levees paralleling the natural channel, and, therefore, only a limited storage could be obtained with an extensive levee system; above this section, because of the shallow valleys of the various tributaries, it would be impracticable to construct separate dams on each of these tributaries. Enough storage could be obtained at the most favorable reservoir site to regulate the outflow from the dam to an inconsiderable discharge, but the location is so far removed from Houston that the run-off from the intermediate area could, under conditions of maximum probable rainfall, produce a run-off large enough to cause flood conditions in the existing channels above and in the city of Houston. Therefore, regulation alone would not furnish complete protection.

61. *Regulation on White Oak Bayou.*—No practicable reservoir site is available on White Oak Bayou within the city limits of Houston due to urban and suburban development along the stream. At a point just north of the city limits, however, a reservoir which would materially reduce maximum probable crest flow could be formed. Local contribution to run-off below such a dam site would not be large. However, as on Buffalo Bayou, even regulated flow could not be accommodated in the present channel and, therefore, channel improvements would be necessary to accomplish full protection.

62. *Diversion.*—Diversion offers the most complete protection of any possible plan inasmuch as it embodies the rerouting of flood waters. It is, however, subject to many natural limitations which govern basic design and indirectly affect the cost. The slope of the water surface in a diversion canal and the depth and quantity of excavation are fixed to a considerable degree by the maximum water levels which may be permitted in the intercepted streams, and the necessary dimensions of the channel are determined from the limiting slopes and the permissible velocities. In the present instance a diversion canal would have to be very long in order to avoid reintroduction of flood waters into the Houston Ship Channel and fairly wide in order to prevent the development of velocities which would endanger its stability, and therefore, the requirements for right-of-way and excavation would be large items and provision for numerous highway and railway bridges would swell the cost. It would be desirable to intercept the various streams as far downstream as possible in order to relieve the present natural channels through Houston from all flow but that which would be dictated by considerations of economy and protection.

63. *Channel enlargement and rectification.*—Enlargement and rectification of the channels of Buffalo and White Oak Bayous to establish capacity for the maximum probable crest discharges would involve large quantities of excavation, the alteration of many of the present bridges or their replacement by larger and more expensive structures, and the design of special works to protect the Houston Ship Channel from the deposit of silt. This improvement would furnish complete protection for the city of Houston from floods in these streams and

some relief for the Houston Ship Channel without great change in the present stream regimen.

64. *Other measures.*—The construction of a settling basin on Buffalo Bayou just upstream from the turning basin as a means of protecting the Houston Ship Channel from the deposit of silt has been considered. However, such a settling basin would have to be of an area and depth comparable to the present turning basin and construction thereof would necessitate the excavation of a great amount of material, including an overburden above mean low water of 20 to 30 feet. Inasmuch as the provision of spoil disposal areas, already difficult to secure within reasonable pumping distance of this vicinity, would be required for the original excavation from the settling basin and for silt deposited therein by floods, it appears that further study of such a work is not warranted.

65. *Conclusions.*—It appears from the foregoing that three general methods of control might be feasible, one with regulation by storage reservoirs as its central feature, another with diversion as its basic part, and a third based on improvement of existing channels. Accordingly, the following general plans, designated plans I, II, and III, respectively, have been prepared.

### PLAN I. REGULATION

66. *Description.*—Plan I includes as its central feature the regulation of the run-off from the maximum probable storm on Buffalo and White Oak Bayous above their junction to an extent which would remove the necessity for enlargement of the channel of Buffalo Bayou between Main Street (junction of Buffalo and White Oak Bayous) and the deep draft turning basin of the Houston Ship Channel. This plan provides for the construction of retention dams on Buffalo and White Oak Bayous and the enlargement of the channels through Houston below these dams, to accommodate the maximum regulated flow together with the run-off from the uncontrolled watershed below the dams. For the regulation of Buffalo Bayou it is proposed to provide a 265,000 acre-foot reservoir. This reservoir will regulate the flow to 15,000 feet per second at a dam site 16 miles (26.8 stream miles) above its junction with White Oak Bayou but the maximum crest flow at the latter point might reach 40,000 cubic feet per second, due to local inflow in the intermediate reaches. The plan provides for the construction of a channel of constant capacity of 40,000 cubic feet per second from the western city limits through the city of Houston to the junction of Buffalo and White Oak Bayous. Between the dam and the western city limits the present natural channel is to be unaltered since overflow to Brays Bayou is prevented by the regulation provided and since the losses due to inundation of this area are inconsiderable. On White Oak Bayou the plan provides for a retention dam, with storage capacity of 35,000 acre-feet, near the northern city limits and a channel varying in capacity from 20,000 cubic feet per second at the dam site to 30,000 cubic feet per second at its junction with Buffalo Bayou. The general features of the proposed dams and their general locations, with typical sections, charts of cost versus control, and operation diagrams for maximum control are shown on plates 7, 8, and 9.

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67. *Results.*—Plan I would afford full protection to the city of Houston above Main Street and would prevent overflow from Buffalo Bayou into the watershed of Brays Bayou. It would completely protect the facilities of the Port of Houston against inundation and the Houston Ship Channel against stages and velocities produced by discharges in Buffalo Bayou above the turning basin greater than 55,000 cubic feet per second. It would also materially reduce silting in the main turning basin and ship channel but would not afford complete protection from the deposit of silt therein.

68. With plan I in operation the peak flood discharges resulting from the storm of December 1935 would have been materially reduced. The maximum discharge would have been about 20,000 cubic feet per second in Buffalo Bayou above White Oak Bayou, 16,750 cubic feet per second in White Oak Bayou, and 35,000 cubic feet per second in Buffalo Bayou between Main Street and the turning basin of the Houston Ship Channel. Loss of life would probably have been eliminated and there would have been little or no damages above Main Street. Below Main Street there would no doubt have been some damage to the railroad bridges, some erosion in the shallow draft channels, and some silting in the deep draft turning basin and ship channel; but these items of damage would have been considerably reduced.

69. The peak discharge which would result from a maximum probable storm on the 267 square miles above the projected dam site on Buffalo Bayou has been estimated at 90,000 cubic feet per second. With a dam constructed on Buffalo Bayou to regulate the discharge at the dam site to 15,000 cubic feet per second, a maximum probable discharge of 40,000 cubic feet per second could occur in Buffalo Bayou above its junction with White Oak Bayou. This discharge would result from the addition to the regulated outflow from the dam of the run-off from the maximum probable storm concentrated over the area below the dam site. Similarly, with regulation on White Oak Bayou the peak discharge at the dam site from the maximum probable storm would be reduced from 45,000 cubic feet per second to 20,000 cubic feet per second, the maximum probable discharge from White Oak Bayou at its mouth would be 30,000 cubic feet per second.

70. With maximum probable crest discharges from the unregulated watershed of Buffalo and White Oak Bayous of 25,000 cubic feet per second and 10,000 cubic feet per second, respectively, and regulated flows in these streams of 15,000 cubic feet per second and 20,000 cubic feet per second there is an indicated combined maximum flow at the junction of Buffalo Bayou and White Oak Bayou of 70,000 cubic feet per second. However, the conditions necessary for creating the maximum probable storm on the unregulated area below both dam sites on the two streams would not be favorable to a large storm on the area above the dam on Buffalo Bayou. Therefore, the discharge from this reservoir, with its large storage capacity, could be completely stopped pending the passage of the peak from the uncontrolled areas. Thus the maximum discharge in Buffalo Bayou below White Oak Bayou could be regulated to not more than 55,000 cubic feet per second, a discharge which the present channel can accommodate with only small damage.

71. Overtopping of the dams is provided against in two ways. First, a freeboard of 5 feet is allowed which represents an increase in

storage capacity of 160,000 acre-feet in the Buffalo Bayou Reservoir and 32,000 acre-feet in the White Oak Bayou Reservoir. This excess storage amounts to 60 percent of the storage required on Buffalo Bayou for control of the design flood, and 90 percent of the similar storage requirements for White Oak Bayou. A second measure of protection is provided for by the installation of culverts having a considerable excess capacity over normal requirements. It was thought better practice to provide for contingencies by an excess storage than to provide excessive spillway capacity, since greater protection from floodwaters would be thereby secured. And it is also to be noted that in the case of emergency a section of the low levees could be breached without endangering the main dam structures. Further, it is considered that the possibility of the occurrence of run-off greatly in excess of the capacities of the reservoirs has been amply discounted in the determination of maximum probable run-off from the watersheds.

72. *Cost.*—The estimated cost of plan I is $21,158,470, the details of which are set out in appendix E.[1]

### PLAN II. DIVERSION

73. *Description.*—This plan provides, as shown on plate 10, for the diversion of Buffalo Bayou floodwaters from a point near the western city limits of Houston south and around the city and thence east to Galveston Bay. Additional features of the plan include: (1) A leveed floodway to convey floodwaters in Buffalo Bayou to the point of diversion, to prevent their overflow into the watershed of Brays Bayou; (2) rectification and enlargement of the channel of Buffalo Bayou from the point of diversion to the junction of Buffalo and White Oak Bayous, and (3) rectification and enlargement of White Oak Bayou Channel through Houston.

74. The diversion channel from Buffalo Bayou to Galveston Bay is designed to carry as a representative figure a maximum of 60,000 cubic feet per second, the leveed floodway on Buffalo Bayou to carry a maximum of 90,000 cubic feet per second, thus preventing the overflow of 30,000 cubic feet per second to Brays Bayou, and the channel of Buffalo Bayou through the city of Houston to carry 30,000 cubic feet per second. A channel through Houston of 45,000 cubic feet per second capacity is provided in White Oak Bayou.

75. *Results.*—Plan II would afford full protection to the city of Houston above Main Street and would prevent overflow from Buffalo Bayou to Brays Bayou. Interests located below Main Street would be afforded considerable relief by the reduction of maximum probable flow in Buffalo Bayou below White Oak Bayou from 90,000 cubic feet per second to 65,000 cubic feet per second. Without the diversion and with the floodway the maximum probable combined crest flow in Buffalo Bayou below White Oak Bayou would be 105,000 cubic feet per second, and the maximum probable crest discharges in Buffalo Bayou and White Oak Bayou individually would be 90,000 and 45,000 cubic feet per second, respectively. The diversion would reduce maximum discharge in Buffalo Bayou from 90,000 cubic feet per second to 30,000 cubic feet per second and would not affect the discharge from White Oak Bayou. The maximum combined discharge below Main Street would be reduced to 65,000 cubic feet per second, a quan-

[1] Not printed.

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tity which would not greatly overtax the capacity of the existing channel. In times of ordinary flood, when the discharge of Buffalo Bayou above the point of diversion was less than 60,000 cubic feet per second, this entire discharge could be diverted and the discharge below Main Street would amount to the discharge from White Oak Bayou plus the small discharge from that part of Buffalo Bayou located below the point of diversion. Thus damages in the city of Houston above Main Street would be eliminated and damages and erosion below Main Street considerably reduced.

76. With this plan in operation the flood of December 1935 would have caused little damage or concern. It would have been possible to divert all discharge in Buffalo Bayou above the western city limits and the maximum discharge from Buffalo Bayou at Main Street would have been about 5,000 cubic feet per second. Maximum discharge from White Oak Bayou would have been about 16,750 cubic feet per second, and the maximum combined discharge in Buffalo Bayou below Main Street would have been about 21,000 cubic feet per second instead of the 53,000 cubic feet per second actually experienced.

77. This plan would have an advantage over plans for regulation or channel enlargement in that it would be possible at such times as the diversion channel was not running full from Buffalo Bayou, to divert flood waters from Brays or Sims Bayous.

78. Plan II has been presented to demonstrate the costs involved in providing a representative diversion canal of any considerable capacity. Several plans with added features have been considered but none were found to be economical. For example, a plan was considered to divert 35,000 cubic feet per second from White Oak Bayou to Buffalo Bayou; but this was found to be more expensive than to provide, as in this plan, for an enlarged and rectified channel to accommodate the entire maximum probable flow of 45,000 cubic feet per second, and the cost of this plan would be further increased to provide the greater capacity that would be required in the diversion canal from Buffalo Bayou to Galveston Bay.

79. *Cost.*—The estimated cost of plan II is $54,686,095, the details of which are set out in appendix E.[1]

PLAN III. CHANNEL ENLARGEMENT AND RECTIFICATION WITH MODIFIED REGULATION

80. *Description.*—This plan provides, as shown on plate 11, for the direction of the floodwaters of Buffalo Bayou and White Oak Bayou through the city of Houston by way of their present channels. Inundation of urban properties bordering the banks of these streams is provided against by enlargement and straightening of existing channels and removal of obstructions to flow.

81. A dam is provided in the same location as on plan I, with storage capacity of 135,000 acre-feet and maximum pool elevation of 98 feet to regulate flow at the dam site to 35,000 cubic feet per second to prevent overflow to Brays Bayou. Thus with maximum probable discharge from the unregulated area below the dam site of 25,000 cubic feet per second the maximum probable discharge in the city of Houston would be 60,000 cubic feet per second and a channel of this capacity is provided from the western city limits to the junction of Buffalo and White Oak Bayous at Main Street. The channel of White Oak

[1] Not printed.

Bayou is improved to carry the maximum peak discharge of 45,000 cubic feet per second and the channel of Buffalo Bayou below White Oak Bayou to carry a discharge of 90,000 cubic feet per second, which is the estimated maximum probable crest discharge from Buffalo and White Oak Bayous together.

82. This plan includes a control structure to raise the floodwater levels at the downstream end of the light-draft channel above the entrance to the turning basin of the Houston Ship Channel. It is contemplated that this structure would be a movable dam with a low-water navigation pass which could be closed in time of flood. The structure would be provided with a paved apron extending some distance downstream to prevent excessive scour in the pool below the structure. It would be operated to raise water levels in the reach above the turning basin in order to reduce the velocity and thereby lessen the erosion of the bed and banks of the stream. By this means erosion would be practically eliminated for all floods of less than 55,000 second-feet discharge, and a lesser measure of protection would be provided against floods exceeding 55,000 second-feet. Since the greater floods occur very infrequently, it is believed that this plan would eliminate the greater part of the silting in the channel, which is principally derived from erosion of the banks in this reach.

83. *Results.*—Plan III would afford full protection to the city of Houston from damages from all floods. However, probable maximum or near-maximum floods, occurring in conjunction with large floods of the San Jacinto River or high tides in Galveston Bay would cause inundation of the wharves and warehouses of the Port of Houston and high stages and velocities would be produced in the Houston Ship Channel by great floods in Buffalo Bayou. The control structure above the turning basin would operate to raise the water surface at the lower end of the light-draft channel and thus to reduce velocities and their damaging effect in this reach, particularly for the ordinary floods which are of more common occurrence. Hence, for all floods as great as have been experienced to date, erosion in the light-draft channel and the deposit of silt from this source in the Houston Ship Channel would be very materially reduced. For larger floods, the probability of which is much less, erosion, silting, and other damages would probably occur, though in less degree than under present conditions.

84. With this plan in operation the flood of December 1935, would have passed through the city of Houston without damage, and, with proper operation of the control structure, little silting would have occurred in the turning basin of the Houston Ship Channel and no overflow from Buffalo Bayou to Brays Bayou would have occurred.

85. *Cost.*—The estimated cost of plan III is $29,134,920, the details of which are set out in appendix E.[1]

## COMPARISON OF PLANS

86. From the foregoing discussion it appears that plan I providing for regulation and channel improvement affords the best solution for the lowest cost. It is therefore considered to be the most practicable plan and the further discussion in this report will be in the main centered on this plan. It is believed that any project adopted should specify only the general features of channel improvements and regulation in order to provide elasticity in the perfection of fully detailed construction plans.

[1] Not printed

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WATER CONSERVATION, POWER, IRRIGATION

87. There is little sustained flow in the streams under consideration and, therefore, it would not be feasible to coordinate flood control with plans for the conservation or development of water resources for power, irrigation, or other purposes.

ECONOMICS

88. *Tangible damages.*—To estimate the average annual damages that would be prevented by the adoption of plan I requires a knowledge as to probable frequency of future floods as well as a knowledge of their damaging effect. In the absence of any exact knowledge as to flood frequency on this watershed it has been estimated, as set out in paragraph 22 above, that in the next 50 years the maximum probable flood will occur once and that floods similar in size to the 1935 flood will occur once in 10 years. On the basis of these frequencies the following paragraphs contain an estimate of the probable extent of flood losses that would be prevented by plan I.

89. *Damages to United States.*—It has been brought out that the average annual deposit of silt in the turning basin and below, attributable to Buffalo Bayou, has been about 420,000 cubic yards during the past 8 years. It may be assumed that, without control on Buffalo Bayou, this annual rate of silting will continue; and a major flood once in 50 years would probably increase the average to 440,000 cubic yards per annum. Dredging costs are high in this section of the Houston Ship Channel and may be expected to average 20 cents per cubic yard. It is estimated that plan I would effect a reduction of 50 percent in the deposit of silt from Buffalo Bayou and would thus save the United States an average annual expenditure of about $44,000 in dredging costs.

90. *Rural areas.*—It appears that the only flood loss which might be suffered in Harris County outside of Houston and the Houston Ship Channel would be through damages to crops. Damages to crops vary with the seasons and it is probable that they were slight in 1929 and negligible in 1935. The 1929 flood occurred in May, when most crops could sustain inundation with limited loss, and the 1935 flood occurred in December, after all crops had been harvested. In view of the fact that the soils of the watersheds of Buffalo and White Oak Bayous are not highly productive, it is not probable that crop losses would at any time attain a very large figure, and it is doubtful how much damage could be attributed to flood as against poor drainage.

91. *Damages to urban areas.*—The tangible damages in the city of Houston due to floods on Buffalo and White Oak Bayous, as reported by the Houston Chamber of Commerce, amounted to $1,392,442.76 in 1929 and $2,528,606.31 in 1935, a total of $3,921,049.07, which is considered a fair figure and so accepted. These figures include damages to public and private properties and stocks. It is estimated that under present conditions the maximum probable flood would cause a loss of not less than $10,000,000 in tangible damages and that each of the assumed 10-year floods would cause damages of $2,500,000. On this basis the tangible flood damages in the city of Houston during the next 50 years would average about $450,000 per annum.

92. Losses due to interruption of transportation and utilities are suffered to the greatest extent by individuals who, as a result of flood, are unable to reach their places of business or whose businesses shut

down during the flood period. Buffalo Bayou traverses the heart of the city and thus separates the mainly residential White Oak section from the commercial district of Houston on the south of the bayou, so that these losses are undoubtedly high. It is estimated that losses due to business interruptions and the loss of wages due to lack of communications and business suspensions would amount to approximately $3,000,000 in a period of 50 years, or an average of $60,000 per annum. In preparing the above estimate consideration has been given to the fact that losses due to interruption of business are to some degree neutralized by increased business in the period of rehabilitation after the flood period.

93. *Damages to the port of Houston.*—The port of Houston has experienced flood damages in delays to shipping, diversion of commerce, and the additional cost which it must assume of providing spoil-disposal areas for the silt that accumulates in the ship channel. It is estimated that losses to shipping due to the delays occasioned by floods, on the basis of present vessel traffic, would amount to about $20,000 per year. Local interests allege that considerable loss to the port occurs by reason of the diversion of cargo during flood periods and state that apprehension as to the delays caused by floods reduces the business of the port. It seems probable that in the great majority of instances the memory of the flood threat is very short-lived, especially since the facilities of the port offer a favorable outlet for the commerce, and it seems that, with the many commercial enterprises and terminal facilities which have been located on this waterway, the port of Houston would never suffer a material diversion of its commerce on account of the small delays and inconveniences caused by floods. Therefore, no allowance is made for this item.

94. The Harris County Houston Ship Channel Navigation District is at the expense of providing large areas of expensive land near the turning basin for the disposal of materials dredged from the Houston Ship Channel. The carrying charges on these lands involve a considerable annual expenditure, which must be provided by the district. If the deposit of silt in the turning basin were decreased 50 percent by improvements for flood control on Buffalo Bayou the area of lands held nearby for spoil-disposal purposes could presumably be decreased by 50 percent and the Harris County Houston Ship Channel Navigation District would be saved approximately $33,000 per year in carrying charges, on the basis of its present holdings.

95. Potentialities exist for damages to warehouse stocks and similar goods because future floods could reach stages above the present wharf and warehouse elevations, but the damage that might be caused under such conditions would depend in large measure on the amount of transient goods in storage and their susceptibility to water damage. Hence it is difficult to evaluate these losses. It is believed, however, that these losses would not be large over a period of years and probably would not exceed $10,000 per annum.

96. *Intangible damages.*—Intangible damages include loss of life, disruption of commerce, and interruption of utilities. Losses of one life in 1929 and 8 lives in 1935 are not properly capable of evaluation but serve to indicate indefinite economic losses attributable to floods. Floods disrupt commerce in many ways, primarily by making bridges, roads, and railways impassable and thus interfering with the movement of personnel and goods. This blocking of the arteries of commerce is felt both in the city of Houston and at the port of Houston.

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The interruption of utilities may be illustrated by the flooding of the central pumping plant of the city of Houston in 1935 whereby one of the main sources of municipal water supply was entirely out of commission for a short time and was forced to operate at reduced capacity pending rehabilitation after the flood. The failure of this pumping plant created a dangerous fire hazard by reducing the pressure in city mains. It is impossible to accurately evaluate these losses, but it is believed that an estimate of $50,000 per year is not excessive.

97. *Summary of benefits.*—From the above discussion of damages it appears that adequate flood protection in Houston, and relief from 50 percent of the deposit of silt in the Houston Ship Channel from Buffalo Bayou would reduce the annual damages to local agencies and individuals as follows:

| *Item* | *Average annual reduction in damages* |
|---|---|
| Property and stock damage | $460,000 |
| Losses to shipping | 20,000 |
| Business suspension and wage losses | 60,000 |
| Dredging costs (including spoil areas) | 77,000 |
| Intangible damages | 50,000 |
| Total reduction | 667,000 |

Allowing a rate of 6 percent, including 4.5 percent as an average rate of interest and 1.5 percent for maintenance and amortization, it appears that relief from the above damages would justify a capital expenditure of about $11,120,000.

98. An additional major benefit would be the enhancement of property values which would result from the installation of flood-control works. A survey of the taxable valuation of property in the flooded area of Houston indicates that successive floods have caused progressive devaluation of property and that the enhancement of property values which would follow the installation of flood-control works to completely protect Houston would amount to approximately $5,000,000.

99. Many of the existing bridges are outmoded or are in an advanced state of physical deterioration or are so ill-adapted to their function that they are in danger of being washed out by a major flood. The replacement of existing bridges which is provided for in the plans described above represents a betterment to existing facilities quite apart from the general question of flood control. Therefore, in considering the economics of a flood-control project it is believed that flood control should be credited with the betterment value of these bridge improvements which is estimated at about $1,000,000 for plan I and $4,000,000 for plan III.

100. Thus it appears that the capital expenditure which is economically justifiable is $17,120,000 for plan I and $20,120,000 for plan III, while the total estimated cost for plan I is $21,158,470 and for plan III $29,134,920. The cost for these plans may be subdivided into construction items and right-of-way items as follows:

| | Plan I | Plan III |
|---|---|---|
| (1) Construction items | $6,721,880 | $12,563,370 |
| (2) Right-of-way items | 14,436,590 | 16,571,550 |
| Total cost | 21,158,470 | 29,134,920 |

In general, the construction items include dams with their appurtenant structures, and all channel improvements including clearing, excavation, paving, etc. The right-of-way items include land acquisition, easements, removal of bridges, relocation of highways and railroads, and other items connected with furnishing the rights-of-way and easements required for the work. The construction items represent the group of expenditures that are to be paid for by the Government under the provisions of the Flood Control Act, while the right-of-way items represent the expenditures that are to be paid for by local interests unless their total shall exceed the construction cost. The items included in each of the above categories are described at greater length in appendix E.[1]

101. Because of the very large sum that is included in the right-of-way items it seems advisable at this stage to present a detailed analysis of these costs. In making this analysis attention will be confined to plan I which appears to be the most feasible. The following table indicates the costs of the individual right-of-way items which are included in the cost estimate for plan I:

*Summary of the estimated cost of right-of-way items, plan I* [1]

| | |
|---|---|
| 1. Land for reservoir sites, 38,720 acres | $4, 893, 000 |
| 2. Land for channel improvement, 888 acres | 3, 849, 400 |
| Total estimated cost of land acquisition | 8, 742, 400 |
| 3. Moving buildings in reservoir sites | 200, 000 |
| 4. Railroad relocations in reservoir sites | 611, 875 |
| 5. Highway relocation in reservoir sites | 288, 000 |
| 6. Railroad bridges, alterations and replacements | 277, 000 |
| 7. Highway bridges, alterations and replacements | 1, 405, 000 |
| 8. Storm sewers, alterations and extension | 25, 000 |
| 9. Engineering, legal expenses and contingencies, 25 percent | 2, 887, 315 |
| Total estimated cost of right-of-way items | 14, 436, 590 |

[1] Summarized from appendix E.

102. It will be noted that the items for acquisition of land, with the allowance of 25 percent for engineering, legal expenses, and contingencies, amounts to $10,828,000, which is very large in proportion to the total cost of $21,158,470 for the project. The land which would be required under plan I is divided into two general categories; (1) land which would be included in retention reservoirs and (2) land bordering the channels through the city of Houston which would be improved.

103. The land which would be included in retention reservoirs has a speculative value, due to its proximity to Houston, in excess of its value for farming or stock raising. This speculative value would be destroyed by the construction of the reservoirs, but the value for farming or stock raising would be only partially impaired because of the relatively infrequent overflow to which the land would be subject. This retained value of the land represents an item which is not properly chargeable to flood control and which should, therefore, be credited to the project. The retained value of these reservoir lands is estimated at $25 per acre or $968,000 for plan I.

104. A part of the land bordering the channels to be improved through the city of Houston is owned by the city of Houston and the remainder by private parties. Practically all of the land owned by

[1] Not printed.

the city of Houston has been acquired for park development, as described in the 1929 report of the city planning commission. It is estimated that the city has acquired and now owns about one-third of the property which would be affected in the flood-control plan. With respect to this city-owned land no outlay of money would be required, and it would in no way be damaged by the proposed work; on the contrary the property would be beautified and improved for its intended recreational purpose. It, therefore, appears, that inasmuch as no expense for acquisition of land would be entailed and no damages would be sustained, the flood-control project should be credited to the full extent of the costs included in the estimates for the acquisition of the city park lands. The approximate amount of this credit is $1,100,000.

105. With respect to the privately owned lands that are included in the proposed park area the situation is somewhat different, but the conclusion as to the propriety of this charge against flood control is substantially the same. The difference lies in the fact that the local agency sponsoring the project must make an outlay of funds for the purchase of these lands. But since these lands are intended to be purchased for park purposes in any event, and since they would not be damaged for this purpose by the flood-control works, but rather improved thereby, it appears that flood control should not be burdened with the cost of their acquisition. The sum of approximately $2,700,000 has been included in the estimate of cost under plan I for the purchase of these lands and this sum may, therefore, be credited to the flood-control project from the standpoint of economic justification, if not from the standpoint of outlay required.

106. In the short section of Buffalo Bayou between Main Street and Capitol Avenue the value of all property used for right-of-way in the flood-control plan, whether privately or publicly owned, would represent a proper charge against the flood-control project inasmuch as the properties in this section are being used for building sites and their appropriation for flood-control purposes would result in actual damages. Hence no credit can be allowed for these items.

107. From the foregoing considerations it is believed that the following items of cost should be deducted from the cost estimate for plan I in order to arrive at the proper charges against the flood-control plan from the standpoint of its economic justification:

| | |
|---|---|
| (a) Credit for asset value of lands in reservoir sites | $968, 000 |
| (b) Credit for park lands now owned by the city of Houston | 1, 100, 000 |
| (c) Credit for privately owned lands to be purchased for flood control but to be incorporated in the city park system as an integral part thereof | 2, 700, 000 |
| Total credit items | 4, 768, 000 |

108. If the credits shown in the paragraph above be deducted from the total estimated cost of $21,158,470 for plan I, the costs properly chargeable to flood control will be reduced to $16,390,470; and since the benefits to be derived from flood control have been estimated at $17,120,000 on the basis of current conditions; and since flood damages would tend to increase with the continued development of the city; and since at least a large expenditure in any event must be made in removing obstructions to relieve the acute flood situation in Houston, it appears that a comprehensive flood-control plan combining channel improvements and regulation is justifiable.

### CONCLUSIONS

109. In view of the foregoing, the district engineer concludes—

(*a*) That protection of the Houston Ship Channel from the deposit of silt contributed by its tributary streams should be considered, at the present time, only in conjunction with the broader problem of flood control on Buffalo Bayou above the deep-draft turning basin.

(*b*) That Buffalo Bayou above the deep draft turning basin of the Houston Ship Channel constitutes, in its present state, a flood menace to life and property in the city of Houston, Tex., and a source of damage and inconvenience to the Houston Ship Channel and shipping therein, particularly in view of the fact that flood discharges greatly in excess of those that have been experienced may occur.

(*c*) That no plan which would afford less than complete flood protection to the city of Houston should be considered.

(*d*) That if the flood-control project must bear the full cost of land acquisition, the minimum cost of any feasible, comprehensive plan for the solution of the flood situation in Houston would be approximately $21,158,470, the cost of a plan (plan I) providing regulation of the headwater flood flows of Buffalo and White Oak Bayous and improvement of the channels of these streams through the city of Houston to their junction.

(*e*) That the flood-control estimate of $21,158,470, for plan I is burdened with costs to the extent of about $10,828,000 for the acquisition of lands which would have a remaining asset value of about $4,768,000 for other uses than flood control and said asset value should therefore be credited against the cost of the flood-control project in determining its economic feasibility.

(*f*) That if the flood-control project be credited with the asset value for other purposes of the lands and easements included in the flood-control estimate, the minimum cost of a feasible, comprehensive plan (plan I) for the solution of the flood situation in Houston would be approximately $16,390,470.

(*g*) That a capital expenditure of about $17,120,000 for flood-control and silt-control improvements would be economically justifiable under plan I.

(*h*) That a flood-control project on Buffalo Bayou for the protection of the city of Houston and the Houston Ship Channel is economically justifiable if the project is relieved of the costs of land acquisition not properly chargeable to the project.

### RECOMMENDATIONS

110. In view of the foregoing conclusions the district engineer recommends that a project embodying the general features of channel improvements and regulation be adopted for Buffalo Bayou, Tex., with a view to protecting the city of Houston and the Houston Ship Channel from floods, at an estimated cost to the United States of $6,722,000 to cover the construction items as described in this report; provided that a responsible local agency will engage, under terms satisfactory to the Secretary of War, to furnish all of the necessary lands, rights-of-way and easements and to do or to provide funds for doing all the work described herein under the classification of right-of-way items; and provided further that, should the cost of the right-of-way items less credits for the asset value of these items for purposes other than flood control exceed the estimated cost of the construction items, the United States may pay one-half the cost of the said excess provided that the total cost to the United States, including the estimated cost of the construction items, may not be made to exceed the sum of $8,560,000 under this provision; and provided further that the Secretary of War shall have final decision as to what portion of the cost of the right-of-way items is properly chargeable to the flood-control project.

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